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Sustainable Valorization of Organic Materials as Substrates for Soilless Crops in Protected Environments in the Venezuelan Andes

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Abstract: Agricultural production activities generate a large amount of waste, most of which is of organic origin from plant remains. These residues could easily be transformed into a resource, specifically, into a substrate for use in soilless cultivation; however, in most cases, they are not used. Therefore, a characterization of local agricultural residues was carried out to determine their use as a substrate for crop cultivation without soil in a protected environment. The selected substrates were *Sphagnum* peat, coir fiber, and compost, which were managed alone or in mixtures of 50/50, 75/25, or 25/75% *v/v* ratios. We also included a mixture of virgin mountain soil and earthworm humus (known as INIA mixture) because it is used by local growers. The results showed that the substrates based on coir fiber, peat, and mixtures of both presented suitable characteristics for horticultural crops. On the contrary, compost-based substrates had high pH values and low organic matter contents that could be improved before use. The relationship found between the evaluated parameters of each substrate allowed us to establish that variables, such as the content of organic matter and water at different tensions and particle sizes, can be utilized to make a quick selection of the substrates produced locally, which would lead to the use of waste in a way that is more consistent with sustainable agricultural production and minimal environmental impact, by being used in the production of crops in containers without soil. In addition, these results can be used as an alternative reference in localities where these residues are easily available.

Keywords: circular agriculture; local resources; peat; coir fiber; compost; vegetable residues from tomato crops



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1. Introduction

Even though the soil is the ideal environment for plant growth, many areas are no longer productive, and studies of local organics materials require time. For this reason, production strategies have been generated, such as soilless crops, which are defined as all those methods and systems that make plants grow outside their natural environment (soil); these strategies seek to recover spaces, positioning them as an alternative to ensure food production for the future, through the most appropriate and sustainable (rational) management of resources [1,2].

The term substrate is applied in horticulture to all solid materials (other than in situ, natural, synthetic, or residual mineral or organic soil), which, when placed in a container in pure form or in a mixture, allows the root system to anchor, thus playing a supporting role for the plant [3,4]. Traditionally, materials have been manufactured to be used as a

substrate (perlite, rockwool, etc.), or organic materials such as peat have been used, in all cases at a high environmental and economic cost.

Some of these materials are used directly, while most require a composting process to be used as a substrate [5–7]. Through the use of these substrates, the waste generated from agriculture can be reincorporated into the system, turning it into a useful resource for agricultural production, thus contributing to solving a waste disposal problem [8,9].

In order to have satisfactory results in terms of germination, rooting, and production in these materials, it is necessary that they present certain physical, chemical, and biological characteristics [10,11]. According to the Regulations European Union on growing media [12], these characteristics include an easily available water retention capacity; sufficient air supply; balanced particle size distribution; low bulk density; stable structure; low cation exchange capacity; sufficient level of assimilable nutrients; reduced salinity; minimum speed of decomposition; and free of weed seeds, nematodes, pathogens, and phytotoxic substances, among others.

Peat (*Sphagnum* peat moss) is among the most widely used substrates worldwide due to its physical, chemical, and biological characteristics, which allow the development of crops [13]. However, the use of these materials has a high cost, and currently, there is limited access to them [14,15]; the extraction of peat also leads to environmental damage to the surrounding areas, which will be against what has been proposed by various countries to combat climate change [16]. Therefore, numerous investigations have focused on the search for substrates, made from local materials from the areas where the substrates will be used, which present characteristics necessary to cultivate the local crops, with low costs and minimal environmental impact. In addition, utilization of these substrates should avoid the use of external materials and be generated locally through the recycling of organic waste to support the local economy, with high sustainability [17,18]. Among the low-cost, locally available substrates in the Andean region are coir fiber, tomato stubble compost, and the commonly used virgin mountain soil, which has not been characterized, and its indiscriminate use is causing erosion and diminishing the sustainability of the area due to the fact that, for the extraction of the soil, it is necessary to deforest the area previously. This INIA mixture includes virgin mountain soil and earthworm, whose extraction requires that the area be previously deforested. This environmental damage also justifies the search for alternative materials.

In this sense, as a general main of this work, local organic materials easily accessible were valued as substrates for soilless cultivation in the search for substrates alternatives to peat, and the mixture of materials contained among its components virgin mountain lands, seeking the sustainability of the area and its ability to support the production of horticultural crops.

2. Materials and Methods

The research was carried out in the Bioenvironmental Laboratory and Compostable Waste Recovery Laboratory of the National Experimental University of Táchira (UNET, San Cristóbal, Táchira State, Venezuela) and in the soil laboratory of Lisandro Alvarado Central Western University (UCLA, Barquisimeto, Lara State, Venezuela), over the years 2018–2019, in which the preparation of physical, chemical, and biological characterization of the substrates were carried out, individually and in mixtures.

For the selection of the materials to be used as a substrate, studies were carried out by our research group with the availability of local organic materials in the area where the experiments for this study were carried out. These materials included fruit, sludge, coir fiber, palm compost, mud from the waste of a beer company, vermicompost from aquatic weeds, and compost from vegetable residues, as well as a mixture used by the National Institute of Agricultural Research (INIA) that corresponds to a mixture of soil mountain virgin and earthworm humus in a 3:1 ratio by volume.

Based on the accessibility for producers, commercial peat, coir fiber, and tomato stubble compost were selected. The latter two are local materials and were selected because

they present easily accessible and low costs for the producers of the region. The materials selected for the study must also be economical to be able to be assumed by the farmers. The mixture generated by the National Institute of Agricultural Research (INIA) was used as a reference substrate to compare soilless mixtures, as it is used by farmers in the area.

2.1. Preparation and Composition of Substrates

Commercially available imported *Sphagnum* peat (Sunshine®) was used in the study. The coir fiber was of local origin; it was washed with water in order to minimize the salt content and then passed through a handmade sieve with 4 mm diameter holes.

The compost was made using chopped tomato stubble, rice husks, and chicken manure, in a ratio of 3:1:1 by volume, respectively. Tomatoes stubble, as a substrate for the study, was collected from the field as residue left after harvesting. It was cut and then passed through a grass chopper in order to obtain small pieces less than 5 cm in size. The rice husk was produced in the central–western zone of Venezuela; it has common use in the Andean region and was complemented with dry and mature chicken manure acquired from poultry production units near the study area. All the materials were mixed and formed into a pile two meters high. To compost the materials, they were covered with dark plastic in order to increase the temperature and initiate the activation of microorganisms that act in the different stages of composting; the pile was turned and mixed every 7 days for four months.

The selected substrates were mixed in proportions that are shown in Table 1.

Table 1. Description of treatments used in the trial.

| Treatments | Composition |
|------------|-----------------------------------|
| T1 | 50%/50% v/v compost–peat |
| T2 | 75%/25% v/v compost–peat |
| T3 | 25%/75% v/v compost–peat |
| T4 | 50%/50% v/v coconut fiber–compost |
| T5 | 75%/25% v/v coir fiber–compost |
| T6 | 25%/75% v/v coir fiber–compost |
| T7 | 50%/50% v/v coir fiber–peat |
| T8 | 75%/25% v/v coir fiber–peat |
| T9 | 25%/75% v/v coir fiber–peat |
| T10 | 100% peat |
| T11 | 100% compost |
| T12 | 100% coir fiber |
| T13 | INIA mix |

Prior to the chemical, physical, and biological characterization, the individual substrates and their mixtures were subjected to humid steam for two hours at a temperature of ± 100 °C to sterilize and disinfect them. This procedure was repeated twice in order to ensure the elimination of all potential pathogens from the crop.

2.2. Characterization of the Substrates

Once the substrates and their mixtures were conditioned, the following analyses were carried out:

Germination Bioassay: This was carried out using the methodology proposed in [19] on the pure substrates. Briefly, the extract is prepared according to Zucconi [20]: a water extract of each compost was prepared by shaking the samples with distilled water at a 1:10 w/v ratio for 1 h, and then filtered. The lettuce seeds (*Lactuca sativa* L.) were placed in an extract filtered for the test. This species is sensitive to the presence of phytotoxic compounds [20], so the phytotoxicity can be evaluated through the germination percentage (%G) and percentage of root length (%LR), through which the germination index (IG) can be calculated: $IG = (\%G \times \%LR)/100$ [21].

Physical characterization: The properties measured include the available water under different stresses, using the sand bed-type stress table methodology proposed by AENOR [22], which allowed obtaining information on the available water at different stresses and the construction of the stress curves and moisture retention (CRH), as well as the evaluation of the ease or difficulty with which water can move within the substrate. We determined the bulk density (Bd), particle density (Pd), total porosity (Tp), contraction volume (CV), water volume (Wv), aeration capacity (AC), buffering water (BW), easily available water (EAW), and remaining water (RW), as well as the different fractions of particles and the index of thickness (% GIr) of each material [23–25].

Chemical characterization: The characteristics evaluated were pH and electric conductivity (EC), which were carried out by passing each of the samples through a 4 mm sieve, to later generate a suspension with water in a 1:5 ratio, on which the pH and electrical conductivity were measured in the same extract [26] with a brand meter Hanna Instrument, as well as Organic matter (OM), through the calcination method at 550 °C [27].

The materials and their mixtures were physically and chemically characterized, taking into account the importance of certain properties when the materials are used in soilless cultivation in containers [2,6]. The physical properties are determinant in the water available at low tensions, and consequently, for irrigation management [6]. The granulometry of the materials directly influences the water:air ratio of the substrates and the tension at which the water available for plants is retained [16]. There are numerous reasons that justify chemically characterizing (EC, pH) the materials that are going to be used as a substrate, since it influences irrigation management and the aging of the substrates [7].

2.3. Experiment Design and Statistical Analysis

The germination tests were performed on saturated substrate extracts of unmixed materials (T10 to T12 (compost, coir fiber, and coconut fiber)) and had 10 repetitions, as established by the protocol and compared with distilled water.

Meanwhile, for the physical–chemical characterization, three replicas of the unmixed materials and the mixtures of the same according to volume were made. The treatments were established according to the percentage of the mixture by volume of each organic material used as the substrate. The 13 treatments (Table 1) include 4 (T10 to T12) that were unmixed materials (compost, coir fiber, coconut fiber, and peat), and were also used for the mixtures that constituted the rest of the 9 treatments (T1 to T9), according to the proportion in the volume and type of material, and it was included the INIA mixture (includes virgin mountain soil) by the frequency of use among farmers (T13).

The treatments (13) were considered as a single factor (substrate), and statistical analysis was performed using the program Rproject, through the lm4 library, and analysis of variance (ANOVA) was carried out using Duncan’s test of means, with the statistically least significant difference (LSD) being expressed as $p < 0.05$.

The results of suction tension, according to the type of substrate included in Figure 1, were carried out using the sand tension table, with the methodology described in the AENOR European Standards (2008) [28], and [22] for determination of physical properties (apparent density, particle densities, volume of water, shrinkage value).

In addition, we used mixed linear models, which allow establishing a relationship between many variables and a single one—in our case, the different voltage and the available water. The physicochemical properties were analyzed through a principal component analysis (PCA), seeking to visualize which property contributes the most to the quality of each substrate, and which group of variables can identify or highlight desired characteristics of the substrates.

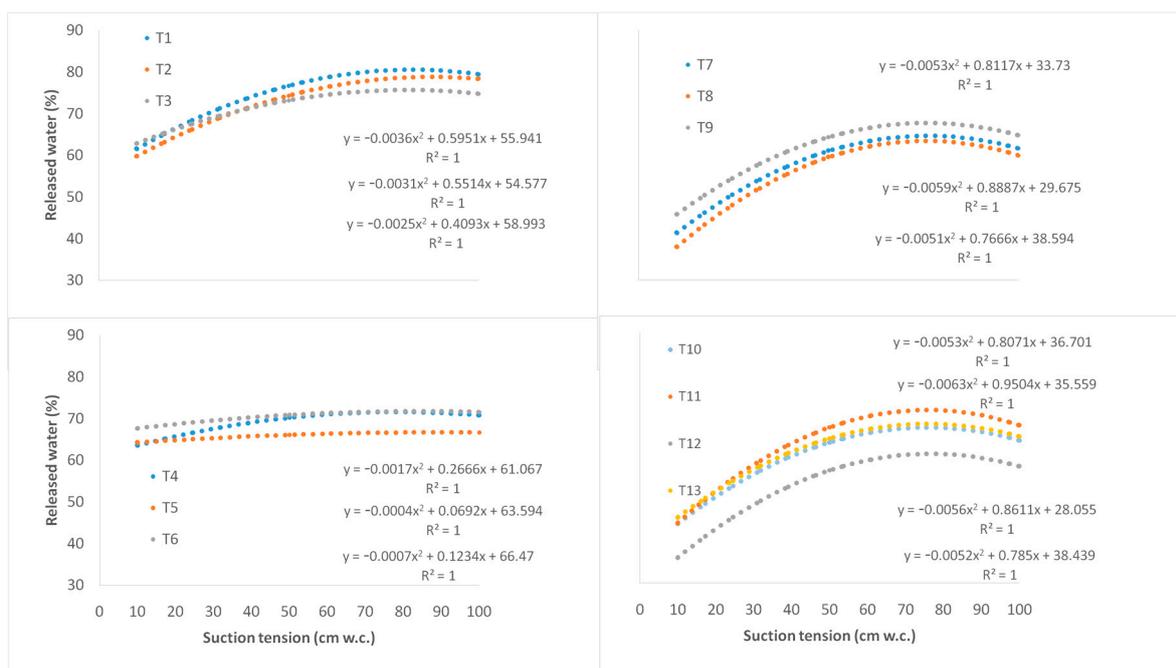


Figure 1. Release of water by the different suction tensions in substrates used. cm w.c. (water column); R^2 , regression coefficient.

3. Results

3.1. Biological Property of Substrates

The evaluation of the biological properties of the substrates, based on the phytotoxicity of their extracts, showed that there was no difference ($p < 0.05$) between the percentage of germinated lettuce seeds, which were above 90% compared to the treatment with only distilled water, which served as a control (100%) (Table 2). However, the germination index (GI), as an indicator of the quality of the substrates and their biological effects, showed an inhibitory effect on lettuce seeds when the compost extract was evaluated, with a value below 50%; meanwhile, the rest of the extracts presented a GI above 80%.

Table 2. Phytotoxicity tests on aqueous extracts of the materials used to prepare the mixtures of substrates with lettuce seeds.

| Sample | Germination (%) | Radicle (Root) Length (%) | Germination Index (%) |
|-----------------|-----------------|---------------------------|-----------------------|
| Distilled water | 100.0 a * | 100.0 a | - |
| T10 | 96.7 a | 91.5 a | 88.4 a |
| T11 | 90.0 a | 37.8 b | 34.0 b |
| T12 | 93.3 a | 99.4 a | 92.8 a |

* $n = 10$. Different letters in the same column for each parameter indicate statistically significant differences ($p < 0.05$).

3.2. Chemical Properties of Substrates

For the pH value, the mean analysis shows a difference between the treatments ($p < 0.05$). Treatments T7, T8, T9, T10, T12, and T13 presented values (Table 3) in a range of 5 to 6.80. The remaining seven treatments all contained compost and had pH values higher than 7.10, indicating that they were slightly basic.

Table 3. Physical and chemical parameters determined in the different substrates.

| Treatment | pH | EC (dS m ⁻¹) | OM (%) | Bd (g cm ⁻³) | Pd (g cm ⁻³) | Tp (%) | WV ₁₀ (%v/v) | AC ₁₀ (%v/v) | CV (%v/v) | EAW (%v/v) | BW (%v/v) | RW (%v/v) | AWC (%v/v) | WR (%v/v) |
|-----------|----------|-----------------------------|---------|-----------------------------|-----------------------------|-----------|----------------------------|----------------------------|--------------|---------------|--------------|--------------|---------------|--------------|
| T1 | 7.30 f * | 0.77 h | 35.13 b | 0.30 h | 2.12 j | 85.81 b | 38.47 a | 47.34 cde | 7.23 e | 15.17 bc | 2.77 d | 20.53 ab | 17.69 | 38.22 |
| T2 | 7.60 g | 0.85 i | 37.96 c | 0.29 h | 2.09 i | 85.97 b | 40.22 a | 45.74 cde | 3.87 c | 14.53 bc | 4.06 e | 21.63 ab | 18.31 | 39.94 |
| T3 | 7.10 e | 0.48 de | 56.51 f | 0.26 g | 1.89 e | 86.29 b | 37.17 a | 49.13 de | 5.27 d | 19.79 c | 1.27 c | 16.11 a | 20.85 | 36.96 |
| T4 | 8.30 h | 0.47 cd | 50.12 e | 0.19 e | 1.95 f | 90.19 b | 36.44 a | 53.75 e | 3.09 c | 6.59 a | 0.58 ab | 29.27 bcde | 7.17 | 36.44 |
| T5 | 8.20 h | 0.76 h | 66.44 g | 0.18 cd | 1.80 d | 90.25 b | 35.75 a | 54.50 e | 1.11 b | 1.84 a | 0.56 a | 33.35 cdefg | 2.4 | 35.75 |
| T6 | 8.20 h | 0.59 g | 41.64 d | 0.21 f | 2.04 h | 89.56 b | 32.37 a | 57.19 e | 3.24 c | 3.20 a | 0.74 abc | 28.43 bcd | 3.94 | 32.37 |
| T7 | 5.00 a | 0.27 a | 80.63 h | 0.18 de | 1.68 c | 89.05 b | 58.68 b | 30.36 b | 1.84 b | 19.68 c | 0.61 ab | 38.40 efg | 20.29 | 58.69 |
| T8 | 5.20 b | 0.53 ef | 83.86 i | 0.17 c | 1.65 b | 89.78 b | 62.03 b | 27.75 b | 5.83 d | 21.46 c | 0.42 a | 40.14 fg | 21.88 | 62.02 |
| T9 | 5.20 b | 0.42 c | 85.68 i | 0.17 c | 1.65 b | 89.66 b | 54.25 b | 35.42 bc | 1.60 b | 18.54 c | 0.45 a | 35.25 defg | 18.94 | 54.19 |
| T10 | 5.80 c | 0.35 b | 64.76 g | 0.12 a | 1.82 d | 93.62 b | 55.26 b | 38.36 bcd | 6.06 d | 22.83 c | 0.46 a | 31.98 cdef | 23.29 | 55.27 |
| T11 | 8.50 i | 0.22 a | 48.94 e | 0.26 g | 1.98 g | 86.75 b | 40.11 a | 46.64 cde | 3.60 c | 9.79 ab | 4.95 f | 25.37 bc | 15.01 | 40.38 |
| T12 | 6.60 d | 0.58 fg | 94.93 j | 0.14 b | 1.58 a | 91.20 b | 63.90 b | 27.30 b | 2.90 c | 20.96 c | 0.93 bc | 42.01 g | 21.89 | 63.9 |
| T13 | 6.80 d | 0.79 h | 16.86 a | 0.84 i | 2.37 k | 64.43 a | 54.23 b | 10.20 a | 0.00 a | 18.98 c | 0.46 a | 34.78 cdefg | 19.44 | 54.22 |

n = 3; Bd, bulk density (g cm⁻³); Pd, particle density (g cm⁻³); Tp, total porosity (%); WV₁₀, water volume (%v/v); AC₁₀, air capacity (%v/v); CV, contraction volume (%v/v); EAW, easily available water (%v/v); BW, buffering water (%v/v); RW, remaining water (%v/v); AWC, available water content (%v/v); WR, water retention (%v/v). * Different letters in the same column indicate statistical differences (*p* < 0.05).

In terms of the CE, there were differences between the substrates and mixtures ($p < 0.05$) (Table 3). Treatments T1, T2, T5, and T13 presented the highest values, while the rest of the treatments show an EC below 0.59 dS m^{-1} ; although there is a difference between the EC values, in all cases, the values found are below what is recommended for use as a substrate of 3 dS m^{-1} . Regarding the OM content, the treatments T7, T8, T9, and T12 showed values greater than 80%, and T13 stood out with the lowest value at 16.86% (Table 3). The highest OM values corresponded to the mixtures that contained coconut fibers (Table 3).

3.3. Physical Properties of Substrates

The results obtained in terms of Bd showed significant differences ($p < 0.05$) (Table 3) among the substrates evaluated, with values between 0.12 and 0.30 g cm^{-3} in most treatments, except for T13, which had a value of 0.84 g cm^{-3} . In terms of the particle density (Pd), all the evaluated treatments presented differences between each other ($p < 0.05$) (Table 3), with only T8 and T9 or T5 and T10 being similar to each other, but different compared to all the treatments.

The total porosity (Tp) of the substrates, expressed through the relationship between Bd and Pd, showed similar values ($p < 0.05$) in most of the treatments, except for T13 (INIA mix); thus, all the mixes had a high Tp value that is optimal for its use as a substrate in a container. The incorporation of coconut fiber into the mixtures contributed to an increase in the porosity of the substrate. When relating the results of Tp to those of Bd and Pd (Bd, bulk density (g cm^{-3}); Pd, particle density (g cm^{-3})), there was an inverse linear relationship (1) ($R^2 = 0.99$) between Tp and Bd, while its correlation with Pd was low (2) ($R^2 = 0.55$).

$$\text{Tp} = 96.99 - 38.78 \times \text{Bd} \quad (1)$$

$$\text{Tp} = 131.19 - 23.27 \times \text{Pd} \quad (2)$$

The retention of water in substrates is fundamental for the sustainable production of crops. There are various metrics for the water levels in the substrates, including their retention capacity for a volume of water (Vw10%). The results found that the treatments formed two groups ($p < 0.5$) with different Vw10% values. Treatments T1, T2, T3, T4, T5, T6, and T11 comprised one group and contained compost as a common component.

In terms of the aeration capacity or aeration percentage (AC), significant differences ($p < 0.05$) were observed between the evaluated treatments (Table 3), among which, T13 had the lowest percentage (10.20), and treatments T4, T5, and T6 showed the highest percentages. When relating this AC parameter to the other measured variables, an inverse linear relationship with Wv ($R^2: 0.96$) (3) was obtained. The AC values of all the substrates were in the optimal range, with the exception of T13, for use as substrates for crops. The incorporation of coir fiber in the mixtures was found to improve the aeration characteristics of the substrates.

$$\text{AC} = 84.392 - 0.9001\text{Wv} \quad (3)$$

One of the important physical characteristics that a substrate must have, according to the literature [29], is volume shrinkage (CV), which should be below 30%. According to the results obtained from the tests carried out, there was a difference ($p < 0.05$) among all the evaluated treatments (Table 3), presenting percentages of volume loss up to a maximum of 7.23%.

Easily available water (EAW) is defined as the percentage of water released by increasing the tension from 1 to 5 kPa, from a 10 to 50 cm water column [6]; these hydric conditions are considered optimal for plant growth. The results obtained show that the EAW values ranged from 1.84% to 22.83% (Table 3), with treatments T8, T10, and T12 presenting the highest percentages. The statistical analysis found that these three treatments were similar to treatments T1, T2, T3, T7, T9, and T13, although the latter group present EAW values less than 20%. On the other hand, the lowest percentage of EAW was presented by T5 at

1.84%, which, together with T4, T6, and T11, did not present statistical differences and are too low to be used as substrates.

Buffering water (BW) is the volume of water that is released when the suction tension in the substrate increases from a 50 to 100 cm water column. The treatments showed differences in BW ($p < 0.05$), with treatments T2 and T11 (Table 3) having the highest values, while T8, T9, T10, and T13 had the lowest. The sum of EAW and BW is the TAW (total available water), a characteristic that is essential to know for the use of the material as a substrate for a container. The T1, T2, and T3 mixtures of compost with peat reached TAW values close to 20% by volume, a sufficient value for use as a substrate. In the volume of remaining water (RW), there were statistically significant differences ($p < 0.05$) among the evaluated treatments (Table 3), with the highest percentages of RW found in treatments T7, T8, T9, and T12, which are formed by a mixture between coir fiber and peat or only coir fiber. Treatments T1, T2, and T3 had the lowest volume of RW. The measurements obtained from EAW and BW allow the determination of the total available water AW (EAW + BW); values within the interval 15.01% to 23.29% were calculated for most of the treatments, except for T4, T5, and T6, which had values below 7.17%. Regarding the total retention of TWR water, which is the sum of EAW, BW, and RW, it was observed that treatments T8 and T12 stood out with values above 60% (Table 3), while all those containing compost (T1, T2, T3, T4, T5, T6, and T11) presented lower values between 32.37% and 40.38%.

The results, based on the release of water for the different substrates according to the suction used (10, 50, and 100 cm c.a.), can be described by means of a second-degree polynomial equation (Figure 1). All treatments had an adjustment coefficient of 1, so the equations explained the behavior of the released water perfectly for each substrate.

The different particle size fractions present in the evaluated substrates showed a statistical difference in the mass percentages (Table 4). In general, the results showed that none of the treatments had particles larger than 25 mm, since their percentage was <0.5%. The percentage of particles between 25 and 12.5 mm was low for most of the treatments, being between 0.05% and 5.27%, except for T5, which presented a value of 22.88. In the same way, the results for the lower end of the size distribution showed that the content of particles smaller than 0.25 mm in the different substrates presented values below 2.56%.

Individually, no significant correlations were obtained between any particle size and the water released by the substrates in the different suction pressures used. However, when relating the suction pressure and the sizes of the particles of the different substrates with the percentage of water released by them using a multiple regression analysis, a significant general model was obtained ($p < 0.05$) ($R^2 = 0.92$), where all the components jointly influenced the determination of % released water (4). Therefore, the percentage of water released can be calculated based on the different particle sizes. Similarly, based on the coefficients for each particle size in the equation, it was observed that the largest coefficient was presented by particles >25 mm, while the rest of the sizes showed similar coefficients. This makes this size the one that contributes the most to the equation in terms of water release, and relates % released water to the amount of macropores that can be added to the mix.

$$\begin{aligned} \% \text{ released water} = & 625.41 - 19.09 (\% \text{ particle } ^1 < 25 \text{ mm}) - 5.7 (\% \text{ particle } 25\text{--}12.5 \text{ mm}) - 5.52 (\% \text{ particle } 12.5\text{--}6.3 \text{ mm}) \\ & - 5.93 (\% \text{ particle } 6.3\text{--}5 \text{ mm}) - 5.69 (\% \text{ particle } 5\text{--}2 \text{ mm}) - 6.26 (\% \text{ particle } 2\text{--}1 \text{ mm}) \\ & - 6.33 (\% \text{ particle } 1\text{--}0.5 \text{ mm}) - 7.36 (\% \text{ particle } 0.5\text{--}0.25 \text{ mm}) - 4.52 (\% \text{ particle } <0.25) - 0.17 (\text{ suction } R^2: 0.45) \end{aligned} \quad (4)$$

¹ Percentage by weight of particles according to diameter (d en mm), water column suction pressure (cm of wc).

Table 4. Weight percentages of different granulometric fractions of the evaluated substrates according to particle diameter and IGr.

| Treatment | Diameter of Particles Present in the Substrates (mm) | | | | | | | | | IGr (%) |
|-----------|------------------------------------------------------|---------|-----------|-----------|----------|----------|---------|----------|------------|---------|
| | >25 | 25–12.5 | 12.5–6.3 | 6.3–5.0 | 5.0–2.0 | 2.0–1.0 | 1.0–0.5 | 0.5–0.25 | 0.25–0.125 | |
| T1 | 0.17 a * | 0.05 b | 9.71 de | 20.82 de | 56.73 a | 8.51 abc | 2.13 a | 1.43 ab | 0.09 ab | 95.99 |
| T2 | 0.22 a | 0.59 b | 16.99 cde | 26.00 bcd | 42.79 b | 7.53 abc | 1.74 a | 1.62 ab | 1.78 a | 94.12 |
| T3 | 0.13 a | 6.69 b | 44.74 a | 24.50 bc | 18.7 de | 2.35 c | 0.37 a | 1.88 ab | 0.42 ab | 97.11 |
| T4 | 0.05 a | 5.27 b | 49.79 a | 21.61 de | 10.72 e | 6.33 bc | 4.13 a | 2.00 ab | 0.09 ab | 93.77 |
| T5 | 0.13 a | 22.88 a | 29.32 bc | 23.23 de | 17.46 de | 6.01 bc | 0.41 a | 0.47 ab | 0.06 b | 99.03 |
| T6 | 0.01 a | 0.40 b | 49.43 a | 18.50 de | 14.59 e | 11.15 ab | 3.39 a | 1.94 ab | 0.11 ab | 94.08 |
| T7 | 0.13 a | 2.53 b | 41.42 ab | 32.29 abc | 13.07 e | 9.46 ab | 0.61 a | 0.45 ab | 0.03 b | 98.9 |
| T8 | 0.02 a | 0.26 b | 14.65 cde | 25.00 bcd | 54.57 a | 2.87 c | 2.34 a | 0.21 b | 0.04 b | 97.37 |
| T9 | 0.05 a | 0.17 b | 4.65 ef | 32.42 abc | 56.04 a | 3.63 c | 1.55 a | 0.84 ab | 0.63 ab | 96.96 |
| T10 | 0.03 a | 0.07 b | 22.27 cd | 36.68 a | 35.61 bc | 3.26 c | 1.45 a | 0.38 ab | 0.21 ab | 97.92 |
| T11 | 0.01 a | 0.35 b | 25.21 c | 25.48 bcd | 27.19 cd | 13.31 a | 6.23 a | 1.47 ab | 0.73 ab | 91.55 |
| T12 | 0.28 a | 1.70 b | 21.11 cd | 33.19 ab | 34.00 bc | 6.48 bc | 2.78 a | 0.34 ab | 0.10 ab | 96.76 |
| T13 | 0.01 a | 0.08 b | 3.05 f | 16.06 e | 60.58 a | 10.06 ab | 6.99 a | 2.56 a | 0.49 ab | 89.84 |

n = 3; IGr (%), thickness index. * Different letters in the same column indicate statistical differences ($p < 0.05$).

4. Discussion

4.1. Biological Property of Substrates

The origin of the extract gives particular characteristics to each substrate, which inhibits or promotes the germination and root growth of each particular species of crops [30,31], which makes the study of these characteristics important. This behavior can be observed among the substrates used in terms of the inhibition generated by compost and the promotion by peat and coir fiber, which shows the importance of evaluating the effect that these substrates and their possible mixtures may have on each plant species.

4.2. Chemical Properties of Substrates

pH is one of the chemical characteristics that must be taken into consideration when using substrates for agricultural production; the ideal range, as reported in the literature, is between 5.5 and 6.8 [3]. Six of the substrates tested in this study were within the established range, and due to this characteristic, they can be considered potential substrates for use in agricultural production. This parameter is susceptible to being corrected, so that in the substrate, it becomes a variable to be considered manageable, because it can be corrected during cultivation with the application of a nutrient solution with an acidic pH [32]. Similar results were found in the literature, where, depending on the origin of the waste, there were different pH values that may or may not be within the desired range [11,33]. In the same way, various authors suggest that pH levels generally increase during the composting process, depending on the material used, for which this parameter should be reviewed during the generation of substrates for crops [34].

In terms of the EC, the different substrates evaluated had parameters values in the range suggested in the literature for substrates (0.74 to 2 dS m^{-1}) [33], which would ensure safety during the application of nutritive solutions, without damaging the development of the plants or creating problems due to salinity [33]. For the proper management of irrigation and adequate nutritive solutions, the use of substrates with these low EC characteristics would be the most highly recommended as substrates for crops [1].

The OM analysis showed that only four of the substrates (T7, T8, T9, and T12) showed higher values than those recommended in the literature for use as a substrate for crop production (higher than 80%) [4,34]. In the rest of the treatments, all the mixtures that contained coconut fiber alone or with peat had values below this reference value. Different authors have stated that reference values can vary; however, depending on the management and crop, these results can be satisfactory [35]. This variable is considered important, so it optimized based on the buffering capacity of the organic material, conferring the substrate with biostability, which allows it to maintain its physical and chemical properties over time [35].

4.3. Physical Properties of Substrates

Chemical properties, such as pH and EC, if necessary, can be managed and corrected by the type of nutrient solution used; however, once the material is in the container and the crops are growing, it is difficult to make corrections to the substrate's physical properties, so the prior evaluation of these is of the utmost importance.

The treatments showed low Bd values, which was consistent with the values reported in other investigations for these types of materials (peat and coconut fiber) [36]. In general, most of the substrates and mixtures evaluated were below the reference value for substrates, which consider optimal values those less than 0.4 g cm^{-3} . All the mixtures were light mixtures, a favorable characteristic to reduce transport costs, when they depend on volume, but not weight.

On the other hand, the Bd values obtained were close to the reference value described in [6,11], which showed that plants grown outdoors should be grown in heavier substrates with a Bd value between 0.50 and 0.75 g cm^{-3} . On the other hand, the use of coconut fiber in mixtures with organic substrates, such as compost, decreases the Bd with increasing volume, a relationship similar to that found in [34]. This is based on the low density of this material, which would allow better management in different crop contexts.

Regarding the particle density (Pd), several studies, including [6], suggest a Pd of 1.45 g cm^{-3} for organic materials and 2.65 g cm^{-3} for mineral materials. All the substrates evaluated were slightly above these reference values for these types of materials. The two density parameters, Bd and Pd, are related to other parameters, among which the moisture retention capacity stands out, which, in turn, depends on the granulometry, porosity, shape, and size of the particles [37].

The total porosity (Tp) of the substrates, according to different authors, must be above 85% of the volume of the substrate [38], which is a reflection of the relationship between Bd and Pd. Most of the treatments, except T13, presented a total porosity above the established reference value and were similar to those found by other authors for organic materials, where values higher than the reference were reported [39].

The equation relating Tp and Bd was also proposed by other authors, where they derived Equations (5) and (6) [6,40] with coefficients that were closely related in terms of magnitude to the ones obtained in this study.

$$Tp = 95.83 - 32.43 \text{ Bd} \quad (5)$$

$$Tp = 98.39(\pm 0.26) - 36.55(\pm 0.36) \text{ Bd} \quad (6)$$

However, there are other studies using composted materials or depending on the characteristics of the origin of the organic material used in the substrates, which showed that Bd decreases the Tp values [35]. This behavior was observed in the use of compost alone or mixed with peat; even when the latter has a high percentage of Tp, its mixture with compost did not have a high Tp value. On the contrary, apart from peat, which is an inherently high-porosity material, all individual or mixed treatments that contained coir fiber show the highest Tp values.

This response may be due to a high value of average diameter (Dm) of the coir fiber particle, as reported by [41]. Variations in porosity are due to various factors, such as the shape, size, and type of pores, and the grinding and sifting practices [42]. The combination of different materials and the proportions of each one generate different shapes and sizes of pores, which can affect the air–water relationship.

The use of new local materials as a substrate must be supported by the physical, chemical, and biological characterization of the materials, which allows the efficient use of water and the harmless reincorporation of waste into the environment [43]. Water management in soilless cultivation methods with a substrate is essential for sustainable production. With respect to the water levels required in the substrates, the capacity that these have for water retention or volume of water (Vw10%) should be optimized between 55% and 70% [2]. Only four of the substrates tested in this study met this requirement. The breadth of the results obtained for this measure was similar to that obtained by other authors [44], which could be related to the characteristics of the organic materials used in the formulation of the substrate.

In terms of the aeration capacity or percentage of aeration, most of the treatments had values within the range referenced in the literature, 20–50% [45]. Those with values above this reference range contained compost and, therefore, rice husks, which causes the formation of larger pores and, consequently, a capacity for higher levels of aeration.

On the contrary, the low percentage of aeration in the other substrates, for example, in the T13 (INIA mix), suggests limited oxygenation of the root system of the crop, possibly leading to root asphyxia in successive campaigns. The results obtained were similar to those obtained by other authors in evaluations of various substrates, where the percentages ranged from 2.8% to 74.1% [35]. The correlation between Bd and Tp was similar to that found in [39], which would allow the determination of one parameter when the other is measured, and thus shortening the evaluation process.

One of the important physical characteristics that a substrate must present, according to the literature, is volume contraction (VC) [6,29], which corresponds to the compaction that the substrate undergoes after a cycle of cropping, which modifies the substrate's

physical properties and directly influences the management of irrigation with the use in successive crops [7]. The variations in CV should not be greater than 30% per year [6]. The results obtained showed a very small loss, based on the reference range established for the substrates, indicating the potential use of the different substrates evaluated. This type of behavior was also reported in the literature using different substrates [46].

All the physical parameters determined in this work are related to the available water for the plants grown in containers, since they cannot be subjected to high water stresses due to the limited volume of the medium in which they grow; hence, the determination of the properties to maintain and release water from the substrates is essential [33]. The optimal EAW percentage for substrates is between 20% and 30% [2,6]. However, only a few of the substrates tested in this study had values within this range. Of the mixtures that incorporated local materials, only T3 (peat and compost 50:50) reached a value close to 20% EAW, which indicated that irrigation management must be designed according to the type of material, which is also mentioned in the literature [47].

It is notable that the treatments containing the Sphagnum peat mix had an adequate EAW, particularly the mixtures of peat with coir fiber. These results agree with those in [48], which indicates that the treatments with values very close to the optimum moisture range are the mixtures that contain between 50 and 75% peat. However, the EAW value of peat (22.83%) differed from those presented by other authors, for example, 32% in [35] and 32.6% in [49]. Therefore, it is necessary to consider that the peat presents variable values according to the origin.

The low ODE values in some treatments were associated with the incorporation of CRT in the mixtures, which shows that it is important to know the characteristics of the materials used for the preparation of the mixtures. However, by including peat with 23% EAW in the mix, it managed to increase the value of the mixes. It is important to know the characteristics of the materials used for the preparation of the mixtures. However, it is not predictable how the different components will affect the physical properties of the mixture; the particle size of each component can significantly affect the result [50].

Regarding the BW, whose optimum value is between 4 and 10 (% *v/v*) [43], the treatments T2 and T11 had similar values, and most of the other treatments had lower values. The literature also reports that the BW values vary, depending on the material with which the substrate is made, with values ranging from 1% to 24% [49]. The BW is not a determining value for the selection of substrates for cultivation without soil, as long as sufficient EAW is available [51].

The RW should be between 25% and 31% [52], and may vary, depending on the materials used. According to the results, the highest percentages of RW were found in the treatments that were a mixture between coconut fiber and peat. Similar values, both within the range and outside of it, are found in the literature [43]. Variations in this parameter may be related to the formation of small pores since the presence of these pores makes it difficult to extract water and, as a consequence, increases RW.

The AW, according to different authors, must be between 24 and 40% [2,6]; all the evaluated substrates and their mixtures were below the minimum value of the range. Similar results were presented in [34]; on the contrary, Refs. [35,49] present variable results, and these same authors affirmed that the decrease in AW in organic materials is the effect of the degradation process, in which the parenchyma disappears, inducing a lower imbibition capacity and affecting the available water capacity.

Regarding the total water retention (WTR), the substrates had values in the range between 49 and 71%; however, this is a relative value, because it is the sum of three parameters that should be considered separately in order to understand the water conditions for the plants. For example, in the case where the treatments have WTR values within the established range, the greatest contribution of water is found in the remaining water (RW). For container crop management, only EAW or AW should be considered for irrigation planning [52].

The release of water in the different substrates, as expressed by numerous authors, will depend on the characteristics of the substrates, in particular, the size and arrangement

of the particles. However, it was observed that the mixed substrates containing compost and coir fiber or peat (T1, T2, T3, T4, T5, and T6) showed a percentage of water release from the beginning that was higher than that of the substrates with only fiber and peat (T7, T8, and T9), the unmixed substrates (T10, T11, and T12), and the substrate from the INIA mix (T13), which leads to less water available to plants [53].

In general, the results of the particle size are contrary to those from [43,49], where different organic substrates obtained high relative values in percentages for particle sizes smaller than 1 mm and greater than 1 mm, while in this study, the percentages of particles less than 1 mm were very low, and most particles were greater than 1 mm in size. The literature states that, in coarse textures, the presence of pores greater than 1 mm that retain small amounts of water indicates the substrate will be well aerated [54].

A principal analysis component (PAC) allowed grouping the evaluated substrates and relating them to their physical–chemical characteristics, where the first explains 74.35% of the variability of the data (Figure 2a) and the second 87.52% (Figure 2b). A principal component analysis (Figure 2a,b) allowed for grouping the evaluated substrates and relating them to their physicochemical characteristics. It was observed that T1, T2, and T11 were grouped together and that they are mostly similar. Despite the values obtained for the EC measurements, particle sizes were less than 2 mm; BW, Pd and Bd were not necessarily similar; and T3, T4, T5, and T6 were clustered into a second group, which showed similar values in terms of pH, AC, and particle size values between 25 and 6.3 mm. The members of a third group, containing T7, T8, T9, T10, and T12, were related through the variables of OM, EAW, AW, Wv, particle size from 6.3 to 5 mm, and percentage of total water (TW). Finally, T13 was separated from all the other treatments.

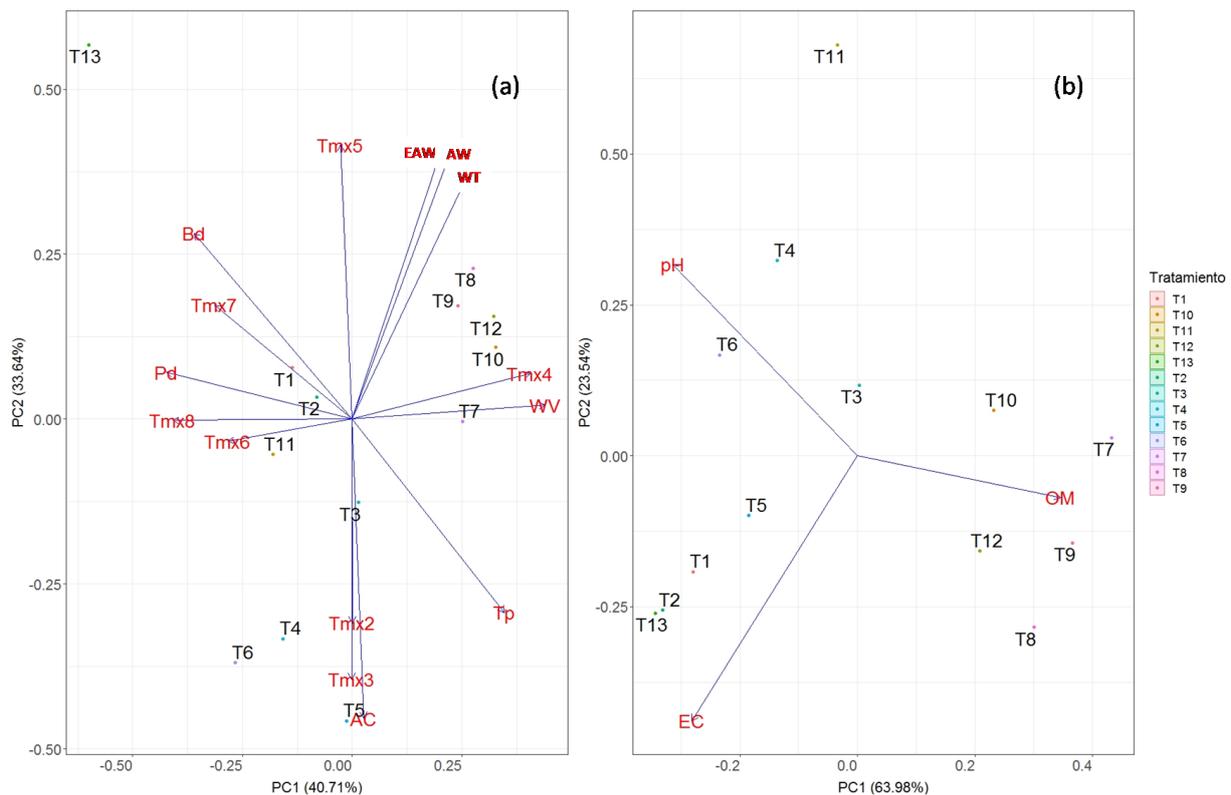


Figure 2. Main components of the different substrate characteristics evaluated. Bd, bulk density; Pd, particle density; OM, organic matter; EC, electric conductivity; Tp, total porosity; Wv, water volume; AC, air capacity; EAW, easily available water; AW, available water; TW, total water percentage; Tmx, particle diameter (mm) = 1: >25; 2: 25–12.5; 3: 12.5–6.3; 4: 6.3–5.0; 5: 5.0–2.0; 6: 2.0–1.0; 7: 1.0–0.5; 8: 0.5–0.25; 9: 0.25–0.125.

Physical characteristics, such as particle size between 25 and 6.3 mm, were related to AC, clearly marking the mixtures that included coir fiber in the compost mixture (T4, T5, and T6). Meanwhile, particle sizes between 5 and 2 mm were associated with the evaluated water content (AW, EAW, and WT). On the other hand, smaller-diameter particles directly influenced the Pd and Bd of the related mixtures and compost, peat, or coir fiber alone, highlighting that the particle size is related to the physical and biological properties, especially with the percentages of water at different tensions.

5. Conclusions

The substrates based on coir fiber, peat, or mixtures of both (T7, T8, T9, T10, and T12) were shown to be ideal substrates, according to the standard ranges of the physical, chemical, and biological properties found in the literature standards for the cultivation of horticultural plants.

On the other hand, the use of mixed models to establish a relationship between the variability of the dependent parameters based on the variability of the independent parameters allowed us to relate the available water to the particle diameter and suction pressure, which shows the possibility of creating release curves or determining water retention based on the study of these parameters, and allowing different stresses to be evaluated.

The grouping of parameters in relation to the type of substrate allows us to establish priorities when evaluating, comparing, and making decisions regarding the use of substrates, which, in terms of OM, RW, AW, EAW, Vw, particle size from 6.3 to 5 mm, and total water (WT), would allow a rapid selection of a substrate. With the results obtained in these physicochemical parameters of the study substrates and that gave the best results or close to the ideals, they serve as a reference when determining the characterizations of other organic materials. They will allow a quick selection if the evaluated substrates behave in a similar way to the results obtained in this investigation.

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