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Development and Validation of Alternative Palm-Derived Substrates for Seedling Production

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Abstract: The constraints associated with peat use in horticulture has led to a search for alternative materials for their use as growing media. The organic materials derived from palm trees (composted or not) can constitute an alternative due to their ligneous and fibrous character, similar to coir fiber. This work studies the feasibility of using several palm-tree-derived (*Phoenix dactylifera* L.) organic materials as growing media ingredients for the transplant production of lettuce (*Lactuca sativa* L. var. Senna). For this, the following substrates were studied: five mixtures for each palm-derived material (palm trunks and leaves and composts derived from palm trunk and leaves), in the proportions of 20%, 40%, 60%, 80%, and 100% by volume, mixed with coir fiber. Coir fiber at the proportion 100% was used as the control treatment. Physical, physico-chemical, and chemical analyses were conducted on the substrates, and the germination and morphological parameters of the seedlings were examined. Chemometric tools, such as random forest (RF) and hierarchical cluster analysis (HCA) were also used to evaluate the data obtained. The type and proportion of material used in the growing media principally affected the parameters studied in the lettuce seedlings. The substrates with a percentage of compost lower than 60% showed behavior closer to that observed in the growing media with 100% coir fiber and with the mixture of coir fiber and palm leaves or trunks at all proportions.

Keywords: compost; *Phoenix dactylifera* L.; horticultural crops; coir fiber; growing media; chemometric tools

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1. Introduction

The maintenance activities of palm species (*Phoenix dactylifera*, *Phoenix canariensis*, *Washingtonia robusta*) generate several residue stream fluxes with an urban and periurban typology, which are not associated to the usual management methods of the agricultural sector. This type of green waste constitutes new residues that municipalities are not still prepared to manage in an integrated and sustainable strategy with several non-standardized options and individual approaches due to the lack of specific European guidelines on these issues. The management of this organic waste usually ends in controlled or uncontrolled burning, principally because of the characteristics of this waste (nature and density) and the absence of pre-treatment and concrete management installations, which implies the loss of the resources contained in them. The burning of organic waste generates different impacts on the environment, especially the emission of GHG gases [1].

Palm orchards constitute one of the rising environmental landscapes in Europe, with a regional specificity; Spain, France, Italy, Greece, and Turkey having more than 95%

of the palm tree area in Europe [2,3]. Pruning of palm represents a huge amount of biomass per hectare in a yearly average. Calculations of the number and extension of palm species in Europe is a goal due the lack of integrated information, but between 20 and 100 million Phoenix species and 10–20 million *Washingtonia robusta* can be estimated in Europe. Considering an average pruning production of 5 kg per year, an estimate is obtained of 500,000 tons of pruning green residue production to be managed [2]. Thus, palm-pruning waste constitutes an important amount of green waste, such as leaves and palm fiber, whose management is an environmental problem [4].

Leaf horticulture, and in particular lettuce production, is a huge sector in Europe. In Spain, around 33,000 ha were planted in 2013, using 2300 million plants and 46,000 m^3 of substrate for seedlings, representing about 20% of total substrate consumption in horticulture, with lettuce being among the top seven most produced horticultural crops [5]. The environmental impacts associated to peat exploitation and its nature as a non-renewable resource have increased the search for alternative materials as growing media [6,7]. Thus, raw fiber materials such as coir fiber (CF) are increasingly used in seedlings and soilless cropping [8]. Coir fiber had, in general, similar to other fiber materials, several good properties for its use as a substrate or substrate components, such as high aeration capacity, low bulk density, and a moderate cation exchange capacity, desirable for most growing media [8]. However, these materials also show several disadvantages, such as a lesser stability, lower water holding capacity, and lower contents of micronutrients compared to peat. Especially, in the case of coir fiber, the higher salinity, the great variability in its physical and chemical characteristics, associated to the source and processing [8] and its production, located in Asian countries, can constitute several drawbacks for its use in Mediterranean countries. Thus, a search for indigenous fibers as an alternative media is still ongoing. Moral et al. [9] reported the feasibility of palm biomass as a raw material for soilless uses. Fornes et al. [10] observed the critical importance of size distribution of constituent particles compared to differences in microstructure and porosity characteristics of coconut coir dust to explain the differential physical properties. Moreover, a great number of studies have been conducted using different organic wastes, especially after composting, reporting an important variability in the results obtained, which depended on the plant species used, the characteristics of the materials, and their proportions in the mixture [7]. Fiber composts, as composts in general, can have physical, physico-chemical, and chemical properties similar to peat that make them suitable peat substitutes. However, these organic materials also can show limiting properties and even potential hazards such as high salinity, phytotoxicity, and/or the presence of contaminants (e.g., heavy metals) [5,7,8]. However, the development of co-composting strategies oriented to quality issues can produce a new generation of compost ready to substitute peat or FC to an increasing degree. Thus, the proportion of the ingredients (in this case fiber raw materials and/or compost) in the formulation of the substrates will also have significant importance in the final properties of the designed substrate, since plant response to different growing media mainly depends on the tested species, but also on the type and proportion of the materials used [7].

Therefore, this work aims to study the feasibility of using different palm tree (*Phoenix dactylifera* L.) derived materials (raw or composted) as growing medium ingredients together with coir fiber in binary mixtures for the transplant production of lettuce (*Lactuca sativa* var. Senna). Additionally, innovative chemometric tools, such as random forest (RF) and hierarchical cluster analysis (HCA) were conducted to identify the optimal properties to predict changes in the growing media according to their composition, as well as to classify the growing media to establish the best combination/s.

2. Materials and Methods

2.1. Experimental Design

Four palm-derived materials were used as components of the growing media studied. These materials were the following: palm trunks (PT) and palm leaves (PL), previously normalized to 0.5 cm in diameter; and two composts derived from this type of waste, LC and TC, derived from palm leaves and trunks, respectively. The main properties of these materials are shown in Table 1. The composition of these composts (on a fresh matter basis) was the following: LC, 72.3% palm leaves + 27.7% sewage sludge and TC, 52.3% palm trunk + 47.7% sewage sludge. Sewage sludge samples were collected after the treatment of wastewater using an aerobic biological process with later stabilization with anaerobic digestion and dehydration using band filters. The composts were prepared using the windrow composting system; more detailed information about the process can be found elsewhere [1]. The composts used had a suitable degree of maturity, in accordance with several chemical and biological criteria [1].

Table 1. Physico-chemical and chemical properties of the ingredients used in the growing media.

Parameter	Coir Fibre	PL	PT	LC	TC
Bulk density (g cm^{-3})	0.072	0.057	0.195	0.306	0.200
pH	6.7	6.3	7.3	6.8	6.1
EC (dS m^{-1})	0.33	1.21	2.61	6.51	5.57
OM (%)	93.3	91.9	85.2	46.3	60.1
TOC (%)	43.4	43.9	32.4	18.8	26.4
TN (%)	0.76	1.34	1.27	1.87	3.35
C/N ratio	57.1	32.8	25.5	10.1	7.88
WSK (mg L^{-1})	357	1347	2694	3046	3575
WSNa (mg L^{-1})	268	397	818	1636	1649
NO_3^- (mg L^{-1})	5.2	4.6	201	6730	13,718
SO_4^{2-} (mg L^{-1})	199	1057	2387	4011	2898
Cl^- (mg L^{-1})	60.4	236	1074	3781	3765

EC: electrical conductivity; OM: organic matter; TOC: total organic carbon; TN: total nitrogen; WSK: water-soluble potassium; WSNa: water-soluble sodium. PL: palm leaves; PT: palm trunk; LC: palm-leaf-derived compost; TC: palm-trunk-derived compost; LC: 72.3% palm leaves + 27.7% sewage sludge; TC: 52.3% palm trunk + 47.7% sewage sludge.

Twenty-one growing media were prepared using the previous materials (PT, PL, LC, and TC) mixed with coir fiber as the diluent in the proportions of 20%, 40%, 60%, and 100% by volume of organic material. A control of coir fiber using ordinary commercial coir, only washed with water (100% coir fiber) was also established. The experiment was conducted at the commercial nursery in the southeast of Spain (Semilleros Baby Plant S.L., Orihuela, Alicante, 38°03′53.4″ N 1°03′15.1″ W).

The vegetable species selected (lettuce, *Lactuca sativa* cv. Senna) were raised in foamed polystyrene plug trays with 322 inverted pyramid cells (one seed per cell). The substrates were settled in a randomized plot design with three replicates per treatment (one tray per replication). Germination was carried out during 3 days in an air-conditioned chamber at 18 ± 1 °C and 85% relative humidity, determining the percentage of germination after 72 h from seeding by counting the number of germinated seeds. Then, the trays were established in a greenhouse with an automatized climate control system (Climatec©, Phoenix, AZ, USA). When the seedlings reached approximately the commercial transplanting size, on day 45 after seeding, 10 seedlings were randomly harvested from each plug tray, avoiding those placed next to the edges. Shoot height and fresh weight were determined prior to washing and drying the seedlings at 60 °C in an air-forced oven for 72 h to calculate dry weight.

2.2. Analytical Methods

In the growing media and initial substrate components (PL, PT, LC, and LC and TC), the physico-chemical parameters, electrical conductivity (EC), and pH were determined in water-soluble extract (1:5, *v/v*) according to the regulations EN 13038 [11] and 12 EN 13037 [12], respectively. Dry matter was evaluated by drying at 105 °C for 12 h, and organic matter (OM) by loss on ignition at 430 °C for 24 h [13]. Total fractions of organic carbon (TOC) and nitrogen (TN) were determined by dry combustion at 950 °C with a Leco TruSpec C–N Elemental Analyzer (Leco Corp., St. Joseph, MI, USA). In the water-soluble extract (1:5, *v:v*), water-soluble fractions of Na and K were determined by flame photometry (Jenway PFP7 Flame Photometer, Jenway Ltd., Felsted, UK) and nitrates, sulphates, and chlorides by ion chromatography (ICS-1000 Dionex, Sunnyvale, CA, USA). In the growing media, the physical properties were studied following the methods detailed by Bustamante et al. [13]. All the analyses were carried out in triplicate.

2.3. Statistical Methods

The Univariate Linear General Model (LGM) with a post-hoc contrast using the Tukey-b test was used to determine if there was an interaction effect between the independent variables studied (type of substrate and compost proportion in the mixture) on each dependent variable (the parameters analyzed). This analysis allows to evaluate the effect of the type and proportion of the materials incorporated in the growing media. In addition, an ANOVA with post-hoc Tukey-b was carried out and included in the Supplementary Material (Tables S1 and S2). This statistical analysis was conducted using the IBM SPSS Statistics v. 27.0 statistical software package (IBM Corp. Released 2020. Armonk, NY, USA).

The chemometric analyses were conducted using random forest (RF) and hierarchical cluster analysis (HCA). RF [14] is an algorithm comprising a group of basic classification models, by using the bootstrap sampling method: multiple samples are eliminated from the original sample, and decision tree modeling is completed for every sample. After the preparation of the training set, each tree casts a unit vote for the most popular class, and the final prediction class is based on the maximum votes rendered by individual predictions [15]. HCA is a technique that studies the classification of samples in groups and among groups depicting a hierarchy [16]. The clusters are formed by samples considered similar according to the recognized pattern. The results are presented in the form of dendograms, which allow visualization of the distances between samples [17]. The R software [18] was used to perform the multivariate analysis. Package "randomForest" [19] and "randomForestExplainer" [20] were used to obtain the multi-way importance plot. The Ward distance was used to obtain the hierarchical cluster using the stats package.

3. Results and Discussion

3.1. Physico-Chemical and Physical Characteristics of the Growing Media

Table 2 shows the effect of the type and proportion of the organic materials used as ingredients in the substrates. Thus, the type of ingredient has a significant effect on both the pH and electrical conductivity (EC) values.

Table 2. Effect of the type and proportion of the organic materials considered for the principal physico-chemical and physical parameters of the growing media.

	pH	EC (dS m^{-1})	TPS (% Vol)	BD (g cm^3)	TWHC (mL L^{-1})	Shrinkage (% Vol)	AC (% Vol)
Optimal Values [1]	**5.3–6.5**	**≤0.5**	**>85**	**≤0.4**	**550–800**	**<30**	**20–30**
Component type							
Coir fiber	6.71b ± 0.16	0.33a ± 0.03	95.2c ± 0.6	0.072a ± 0.001	520c ± 9	14.3b ± 0.4	43.2b ± 0.9
PL	6.20a ± 0.20	1.03b ± 0.22	95.2c ± 0.9	0.072a ± 0.012	299a ± 101	9.9a ± 3.2	65.2d ± 10.8
PT	7.30c ± 0.23	1.82c ± 0.61	90.6b ± 2.3	0.146b ± 0.036	434b ± 34	10.4a ± 2.0	47.2c ± 1.4
LC	6.16a ± 0.20	4.67c ± 1.57	91.1b ± 2.0	0.153c ± 0.037	427b ± 19	17.8c ± 0.9	48.5c ± 0.5
TC	6.75b ± 0.20	4.42c ± 1.67	88.1a ± 3.3	0.221d ± 0.070	597d ± 67	20.6d ± 3.6	28.4a ± 10.0
ANOVA	***	***	***	***	***	***	***
Component proportion							
0%	6.71a ± 0.16	0.33a ± 0.03	95.2f ± 0.6	0.072a ± 0.001	520d ± 9	14.3a ± 0.4	43.2a ± 0.9
20%	6.67a ± 0.59	1.55b ± 0.77	93.6e ± 0.8	0.102b ± 0.015	463c ± 28	15.9a ± 2.3	47.3b ± 3.3
40%	6.57a ± 0.52	2.29c ± 1.22	92.5d ± 1.9	0.123c ± 0.036	457c ± 70	14.2a ± 3.5	46.8b ± 8.8
60%	6.58a ± 0.50	3.15d ± 1.76	91.0c ± 2.7	0.151d ± 0.054	444b ± 113	14.4a ± 5.3	46.7b ± 13.8
80%	6.58a ± 0.49	3.96e ± 2.34	89.9b ± 3.7	0.175e ± 0.078	433b ± 151	14.6a ± 6.4	46.7b ± 18.7
100%	6.61a ± 0.51	3.98e ± 2.29	89.1a ± 4.7	0.189f ± 0.092	399a ± 190	14.2a ± 7.9	49.3c ± 23.5
ANOVA	n.s.	***	***	***	***	n.s.	***

[1] According to Abad et al. [21] and Noguera et al. [22]. EC: electrical conductivity; TPS: total pore space; BD: bulk density; TWHC: total water holding capacity; AC: air capacity. PL: palm leaves; PT: palm trunk; LC: palm-leaf-derived compost; TC: palm-trunk-derived compost. Mean values (n = 20 for the factor component type and n = 16 for the factor component proportion) ± standard deviation. n.s.: not significant $p > 0.05$; ***: significant at $p < 0.001$, respectively. Values in columns followed by the same letter for each factor and parameter are not statistically significant according to the Tukey-b test.

The growing media with the materials derived from palm leaves (PL and LC) showed pH values within the optimal range for a growing medium, whereas the other had pH values slightly higher and close to the reference values, except for the growing media with PT. The type of component had a clear influence on the substrate salt content, due to the great differences observed in the electrical conductivity in the initial materials (Table 1) showing composts with the highest values. Thus, only the substrate with 100% coir fiber had lower EC values than the limit value established [21,22], the substrates with PL showing the lowest EC values of all fiber- or compost-derived substrates. The greatest EC values were found in the substrates prepared using composts (LC and TC), these values being much higher than the EC limit value, due to these materials having the highest EC values, as it has been previously stated. The component proportion in the growing media did not show any effect on the pH values, but influenced the electrical conductivity values, which significantly increased with the percentage of the component in the growing medium, with no significant difference observed between the percentages of 80% and 100%. The incorporation of the raw materials, and especially of composts, which showed high EC values, to coir fiber that had very low EC values (<0.5 dS m^{-1}) (Table 1) clearly suggest an increase in the salinity content of the substrates that was higher with higher presence of each component. Ceglie et al. [7] also reported the same trend in a study of peat substitution using green composts and palm trunk fiber waste, similar to Tittarelli et al. [23] and Ceglie et al. [24] using green waste composts as substrate components. Bustamante et al. [13] also reported the increase in the substrate salinity with increasing proportions of winery waste composts due to the higher EC values of these materials compared to peat, while Bustamante et al. [25] also observed an increase in EC values with higher proportions of compost in the growing media.

Regarding the physical characteristics studied in the growing media, comparing with the ideal substrate requirements established by Abad et al. [21], the ingredients used for seedling media met most standards, with values within the optimal range for each parameter. Bulk density in all growing media was below the limit value (≤0.4 g cm^{-3}), despite the great differences observed between the values of this parameter among the raw materials and composts (Table 1). Composts showed the highest values, this fact being usually and probably due to the different particle distribution and size compared to the raw materials, as well as the presence of inorganic material in compost that also increases bulk density [7,8]. However, water-holding capacity was critical, with average values lower than the reference range, except for coir fiber and the substrates with compost from palm trunk, being especially low for the growing media with palm leaves (PL) (Table 2). Low values of the water-holding capacity are related to a higher particle size of the materials used, also implying a higher air capacity [8]. Ceglie et al. [7] also reported the opposite behavior, higher capacity for water retention and lower air volume for coir fiber and palm trunk fiber waste, as was observed in our experiment. Bustamante et al. [25] observed a change in the physical properties of the substrates, especially a decrease in air capacity and an increase in total water-holding capacity, when the substrate components were previously washed to reduce salinity, probably due to changes in particle size and pore distribution.

The proportion of the components in the substrates also had a significant effect on the physical properties, except for shrinkage. However, in general, a clear trend was not observed depending on the component percentage, this fact was only observed with the parameters BD and TPS. These properties are inversely correlated in the substrates, since low bulk density is associated to high free pore space [7]. This was in accordance with the results obtained for these properties, since BD increased with the increasing proportion of ingredients in the growing media composition, while TPS decreased with the proportion.

3.2. Chemical Characteristics of the Growing Media

Regarding the effect of the type and proportion of the ingredients in the growing media on their chemical properties (Table 3), the substrates prepared using PL and PT showed the highest organic matter (OM) concentrations, similar or slightly lower than coir fiber. This fact is due to the raw materials also having the highest OM contents compared to both composts (Table 1), which is a consequence of the mineralization processes occurring during the composting process.

Table 3. Effect of the type and proportion of the organic materials considered for the principal chemical characteristics of the growing media.

	OM (%)	TN (%)	WSK (mg L^{-1})	WSNa (mg L^{-1})	NO_3^--N (mg L^{-1})	SO_4^{2-} (mg L^{-1})	Cl^- (mg L^{-1})
Optimum Values [1]			**150–249**	**<115**	**100–199**	**960**	**<180**
Component type							
Coir fiber	93.3d ± 0.5	0.76a ± 0.01	357a ± 19	268a ± 16	1.17a ± 0.18	60.4a ± 2.1	199a ± 14
PL	93.2d ± 0.9	1.06c ± 0.19	1239b ± 372	464b ± 95	1.23a ± 0.34	209b ± 28.5	790b ± 196
PT	86.4c ± 2.2	0.99b ± 0.18	1986c ± 639	697c ± 142	22.8a ± 17.9	661c ± 302	1416c ± 686
LC	66.0b ± 7.1	3.05e ± 0.45	2412d ± 869	1024d ± 409	1920c ± 984	3322e ± 714	2034d ± 828
TC	54.6a ± 8.2	1.75d ± 0.17	2825e ± 858	1644e ± 362	1017b ± 653	2792d ± 892	2110d ± 1255
ANOVA	***	***	***	***	***	***	***
Component proportion							
0%	93.3e ± 0.5	0.76a ± 0.01	357a ± 19	268a ± 16	1.17a ± 0.18	60.4a ± 2.1	199a ± 14
20%	81.8d ± 10.9	1.35b ± 0.69	1190b ± 376	717b ± 461	216b ± 129	1003b ± 831	667b ± 193
40%	77.7c ± 14.7	1.56c ± 0.74	1671c ± 549	809bc ± 344	457c ± 435	1687c ± 1489	1124c ± 311
60%	73.7b ± 16.5	1.79d ± 0.97	2237d ± 606	916c ± 412	698d ± 494	1818c ± 1500	1492d ± 566
80%	71.2a ± 19.1	1.89e ± 1.01	2665e ± 938	1125d ± 675	1048e ± 837	2007d ± 1575	2067e ± 920
100%	70.9a ± 19.1	1.96e ± 0.87	2813e ± 862	1221d ± 562	1282f ± 975	2214e ± 1649	2588f ± 1128
ANOVA	***	***	***	***	***	***	***

[1] According to Abad et al. [21] and Noguera et al. [22]. OM: organic matter; TN: total nitrogen; WSK: water-soluble potassium; WSNa: water-soluble sodium. PL: palm leaves; PT: palm trunk; LC: palm-leaf-derived compost; TC: palm-trunk-derived compost. Mean values (n = 20 for the factor component type and n = 16 for the factor component proportion) ± standard deviation ***: significant at $p < 0.001$. Values in columns followed by the same letter for each factor and parameter are not statistically significant according to the Tukey-b test.

On the other hand, the substrates with LC in their composition had the greatest concentration of total nitrogen (TN), much higher than the substrate with 100% coir fiber. The increasing proportion of ingredients in the growing media decreased OM concentrations, finding the opposite trend for TN. The OM decrease with the raising ingredient proportion could be probably due to the higher mineralization grade of several of the components used, especially composts, which is also shown in the initial lowest OM concentrations compared to the raw materials (Table 1). Bustamante et al. [25] reported the same trends in a study using composts from livestock waste as substrate components.

The type of ingredient and their respective proportion in the substrate also showed a significant effect on the water-soluble ions (Table 3). For all the ions studied, the highest concentrations were found in the growing media composed by LC and TC, coinciding with the highest electrical conductivity values found in the substrates with these ingredients, respectively. The increasing proportion of the components in the substrates also increased the concentrations of the water-soluble ions considered (K, Na, NO_3^--N, SO_4^{2-}, and Cl^-), exceeding the limit values established in previous studies [21,26]. This fact could be due to the higher concentrations, especially of NO_3^--N, SO_4^{2-}, and Cl^-, observed in the composts used, probably as a consequence of the use of sewage sludge together with the corresponding palm fiber material to prepare the composts. Carlile et al. [8] also reported high concentrations of these ions in substrates prepared with composts from sewage sludge and municipal solid waste.

Only the substrates prepared with coir fiber, PL, and PT showed suitable concentrations of NO_3^--N and SO_4^{2-}, with values within the adequate range for an optimal substrate [21,26]. Medina et al. [27] also reported a significant increase in the ions from the water-soluble extract when increasing the proportion of spent-mushroom substrates as components in growing media, due to the salt contents of this waste.

3.3. Germination and Morphological Parameters of the Lettuce Seedlings

Table 4 shows the plant response (germination, shoot height, aerial and root fresh and dry weight) with the different substrates. The seedlings grown in the substrates with coir fiber, PL, and PT showed the highest germination percentages, these values being statistically similar among them. The proportion of the ingredients also had a statistically significant effect, decaying the germination with the proportion of component in the substrate, which can be explained by the increasing concentrations of water-soluble ions found, also reflected in the increasing electrical conductivity values. Moreover, the growing media with LC and TC in their composition had the lowest germination percentages, coinciding with the higher salinity contents observed in these substrates and the high contents of phytotoxic elements such as Na and Cl^-, which are usually present in high concentrations in compost derived from sewage sludge and municipal solid waste [8]. This behavior has also been reported by different studies using palm fiber waste and/or composts from green waste [7] and from livestock manure [25] as substrate components. Medina et al. [27] found a significant decrease in the seed germination for the substrates with the highest proportions of spent-mushroom substrates as components in growing media, due to the high salinity of these materials, which produced an increase in water-soluble ions. Concerning the morphological parameters (Table 4), the greatest values of shoot height were observed in the substrates with coir fiber and a proportion of 20% of ingredients (80% coir fiber). In general, shoot height decreased with the decreasing proportion of components, only showing higher shoot height at 20% of ingredients than 0%, probably due to the incorporation of nutrients, such as N and P, with the organic waste and/or composts, as it has been reported in previous works [13,25,28].

Table 4. Effect of the type and proportion of the organic materials considered in the germination and morphological characteristics of lettuce seedlings.

	GI (%)	H (cm)	AFW (g)	ADW (g)	RFW (g)	RDW (g)
Component type						
Coir fiber	99.5b ± 0.2	2.70e ± 0.05	0.29c ± 0.01	0.029c ± 0.001	0.283e ± 0.008	0.029e ± 0.000
PL	99.1b ±1.0	1.18a ± 0.37	0.07a ± 0.03	0.006a ± 0.003	0.063a ± 0.027	0.007a ± 0.002
PT	97.2b ± 3.6	1.80b ± 0.37	0.24b ± 0.04	0.024b ± 0.005	0.207b ± 0.041	0.023d ± 0.004
LC	78.3a ± 31.1	2.59d ± 1.21	0.51d ± 0.28	0.033d ± 0.018	0.266d ± 0.140	0.022c ± 0.012
TC	77.4a ± 31.4	2.33c ± 0.97	0.44c ± 0.22	0.029c ± 0.017	0.222c ± 0.112	0.019b ± 0.009
ANOVA	***	***	***	***	***	***
Component proportion						
0%	99.5c ± 0.2	2.70e ± 0.05	0.29b ± 0.01	0.029d ± 0.001	0.283e ± 0.008	0.029e ± 0.000
20%	99.2c ± 1.1	3.01f ± 1.21	0.51d ± 0.36	0.037e ± 0.205	0.280e ± 0.117	0.025d ± 0.009
40%	98.9c ± 1.2	2.42d ± 0.77	0.39c ± 0.24	0.031d ± 0.016	0.257d ± 0.139	0.024d ± 0.012
60%	98.4c ± 1.6	1.87c ± 0.54	0.31b ± 0.19	0.022c ± 0.011	0.190c ± 0.091	0.018c ± 0.008
80%	84.5b ± 14.8	1.42b ± 0.32	0.20a ± 0.10	0.015b ± 0.007	0.134b ± 0.045	0.012b ± 0.005
100%	58.9a ± 39.0	1.15a ± 0.21	0.15a ± 0.07	0.011a ± 0-006	0.085a ± 0.054	0.010a ± 0.007
ANOVA	***	***	***	***	***	***

GI: germination; H: shoot height; AFW: shoot aerial fresh weight; ADW: shoot aerial dry weight; RFW: root fresh weight; RDW: root dry weight. PL: palm leaves; PT: palm trunk; LC: palm-leaf-derived compost; TC: palm-trunk-derived compost. LC: 72.3% palm leaves + 27.7% sewage sludge; TC: 52.3% palm trunk + 47.7% sewage sludge. Mean values (n = 20 for the factor component type and n = 16 for the factor component proportion) ± standard deviation. ***: significant at $p < 0.001$. Values in columns followed by the same letter for each factor and parameter are not statistically significant according to the Tukey-b test.

Regarding aerial and root fresh and dry weight, the general trend showed a significant effect of the type and percentage of component in the growing media, the substrates with LC and coir fiber showing the highest aerial fresh and dry weight and the greatest root fresh and dry weight, respectively (Table 4). The decreasing proportion of the components in the substrates produced an increase in the values of these morphological parameters, except for the aerial fresh and dry weight, with higher values for the proportion of 20% than 0% of ingredients. Bustamante et al. [25] found this latter effect, with the corresponding proportions of 25% and 0% of compost, probably due to the incorporation of nutrients with the ingredients.

3.4. Chemometric Analyses: Random Forest (RF) and Hierarchical Cluster Analysis (HCA)

The plot corresponding to the random forest analysis of the variables determined are shown in Figure 1.

This figure shows all the variables analyzed and those marked with a black circle are the most relevant variables to explain the proportion of coir fiber in the growing media, which are H, GI, Cl, TPS, and RFW. The tree-based approach random forest (RF), consisting of algorithms based on rule induction that partitioned the dataset space into several class subspaces [14], was conducted to evaluate the variables that are better related to the proportion of coir fiber in the substrate. The p-value corresponds to the increment in the mean squared error (MSE) of the generated trees. In addition, the red points correspond to the variables WSK and ADW, with importance in the analyses (p-value < 0.01), but which appear in fewer trees than the rest of the mentioned variables. This approach shows that the main variables related to the proportion of component in the mixture are mainly morphological parameters, such as the germination, shoot height, and root fresh weight, as well as chemical and physical parameters, chloride and total pore space, respectively. This result of the model coincides with the results observed, related to the lower germination observed in the seedlings grown in substrates mainly with higher contents of chloride (higher salinity), such as LC and TC. In addition, although with a lesser relevance, water-soluble K and aerial dry weight seem to be related to the percentage of coir fiber in the growing media studied.

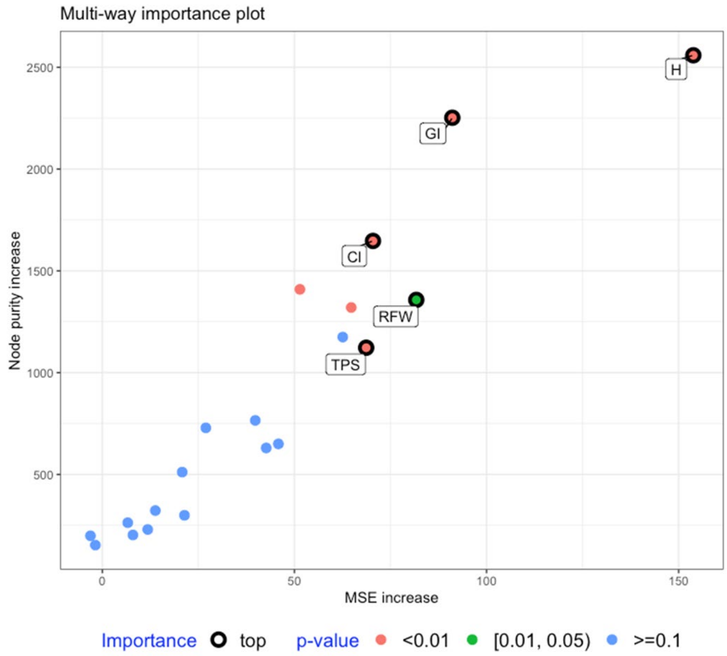

Figure 1. Multiway importance plot of all the parameters studied using the random forest (RF) analysis. MSE: mean squared error; Cl: chloride; GI: germination; H: shoot height; RFW: root fresh weight; TPS: total pore space. The red points correspond to WSK (water-soluble K) and ADW (aerial dry weight). The marked circles correspond to the most relevant variables related to the proportion of coir fiber in the substrates.

Figure 2 shows the dendrogram corresponding to the hierarchical cluster analysis (HCA) of the data obtained from the parameters determined in the substrates and plant seedlings.

This chemometric analysis was carried out to study the possibility of grouping the different growing media based on their similar characteristics, depending on the ingredient incorporated and the proportion used. Similarities and dissimilarities were quantified using square Euclidean distance measurements. The results of HCA showed three main groups. Thus, one of them grouped coir fiber (CF) with the growing media constituted by palm leaves (PL) and palm trunk (PT) at all proportions, showing that these components incorporated in the growing media had similar behavior to coir fiber, considering the parameters studied. Moreover, as Figure 2 shows, when the square Euclidean distances (x-axis) are lower among samples, the more similar these samples are. This model confirms the behavior observed in most of the parameters studied in the growing media and in the lettuce seedlings. The second group is composed of the growing media with compost from palm trunk and leaves (TC and LC, respectively), with proportions of these components similar or lower than 60% and the third group is formed by the substrates with TC and LC in percentages similar or higher than 80% of the component. These results also highlighted the differential effect of the type of material and on the proportion, especially in the case of composts, on the growing media properties and on the plant seedlings characteristics.

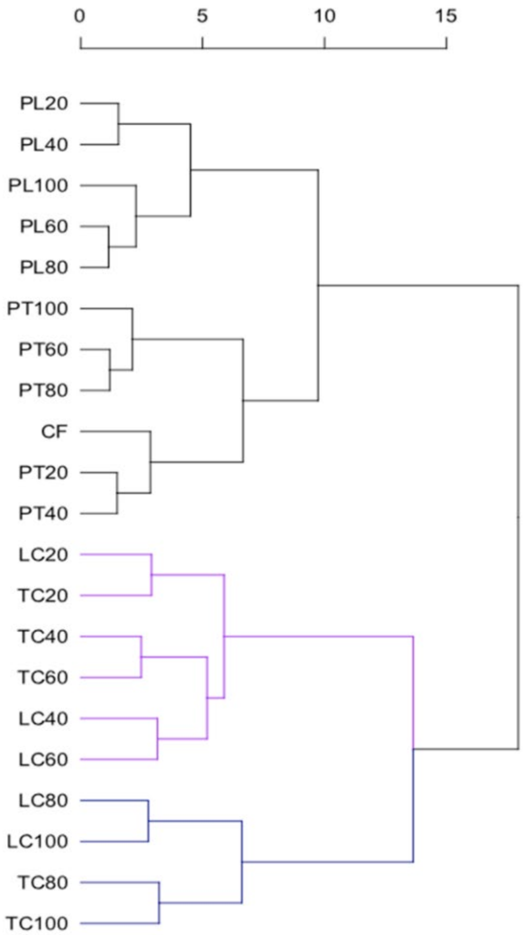

Figure 2. Dendrogram obtained by hierarchical cluster analysis (HCA) of the data of the different parameters studied in the growing media and lettuce seedlings. The *x*-axis represents the square Euclidean distances; PL: palm leaves; PT: palm trunk; LC: palm-leaf-derived compost; TC: palm-trunk-derived compost.

4. Conclusions

In general, the growing media prepared with organic materials derived from palm tree (*Phoenix dactylifera* L.) and coir fiber showed suitable properties for the commercial transplant production of lettuce (*Lactuca sativa* L. var. Senna). The type of and proportion of the ingredients used in the growing media had a clear effect on the substrate properties and on the lettuce seedling germination and morphological characteristics. Lower germination rates were found with the substrates composed of the composts LC and TC and in the highest proportions due to their higher salinity contents compared to the raw fiber materials, which could be a limiting aspect for their use as a substrate component. Only the substrates with LC and TC at proportions lower than 60% had behavior closer to that observed in the growing media with 100% coir fiber. However, the substrates composed of palm leaves (PL) and palm trunks (PT) at all the proportions showed the most similar characteristics and effects on plant response to coir fiber, without any negative effect on the germination and morphological plant parameters. In addition, the chemometric tools used (RF and HCA) allowed to identify the variables that were better related to the proportion of coir fiber in the substrate and to group the growing media that were more similar to coir fiber (PL and PT).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12061377/s1, Table S1: Physical, physico-chemical and chemical characteristics of the substrates studied analysed with ANOVA and post-hoc Tukey-b test. Table S2: Germination and morphological characteristics of lettuce seedlings grown in the substrates studied analysed with ANOVA and post-hoc Tukey-b test.

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