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Physical Properties of the Canary Islands' Volcanic Pyroclastic Materials as Horticultural Substrates

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Abstract: In the Canary Islands and in other parts of the world where it can be found in its natural state, basaltic tephra, or "*Picón*" as it is known locally, is commonly used as a soilless substrate for crops. The aim of this study is to learn more about the physical properties of the Canary Islands' tuff, and to find a simple method to predict the hydraulic behaviour of these substrates due to their heterogeneity. To accomplish this, 32 tuff samples were collected from all the quarries on the island of Tenerife (Canary Islands) that were authorised for the study. The tuffs had hydraulic properties that were highly influenced by the particle size. Coarse tuffs had an aeration capacity greater than 35% v/v and easily available water of less than 5% (v/v), while fine tuffs had aeration capacities below 20% v/v and elevated water retention (20 to 26% v/v). The intermediate tuffs had characteristics that varied between those of the two previous groups. Particle size fractions of less than 1 mm demonstrated the best correlation to common air:water ratios and present the best predictive capacity to relations involving air. By focusing on air:water ratios and the previous assumption, an attempt was made to predict the suitability of new pyroclastic material samples emitted by the La Palma Volcano as growing substrates for vegetables.

Keywords: volcanic ash; tephra; scoria; tuff; air–water relations

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1. Introduction

One of the main advantages of soilless cultivation is its ability to simultaneously provide adequate levels of oxygen and water to roots. This ability depends on the physical properties of the substrate, and optimal irrigation control can be achieved if these properties are well established [1]. The pore size distribution is directly related to the air–water ratio [2,3]. Many successful attempts have been made to correlate air–water relations with certain granulometric characteristics [4–8].

"*Picón*" is the local name used to refer to the basaltic pyroclastic material or tephra found in the Canary Islands (Figure 1). This material has been used as a substrate for soilless crops since the 1960s [9–11]. These materials are also used in other places [12], such as Israel (using the English term tuff) [13], Turkey (tuff, same as above) [14], France (puzzoulana) [15], Mexico (tezontle) [16] and New Zealand (scoria) [17].

In being a local resource, this material has a series of interesting characteristics, such as a low cost, a reduced carbon footprint [18], a very long life cycle [19] and the ability to improve the organoleptic quality of some crops [20]. Tephras, however, are heterogeneous materials, so their characteristics can vary significantly between each batch employed.

There are a number of studies on the chemical properties of tephras from the Canary Islands [21–24], but there are not as many that refer to their physical properties [10,25]. This differs from studies of the physical properties of similar materials performed in other places [16,26–28].

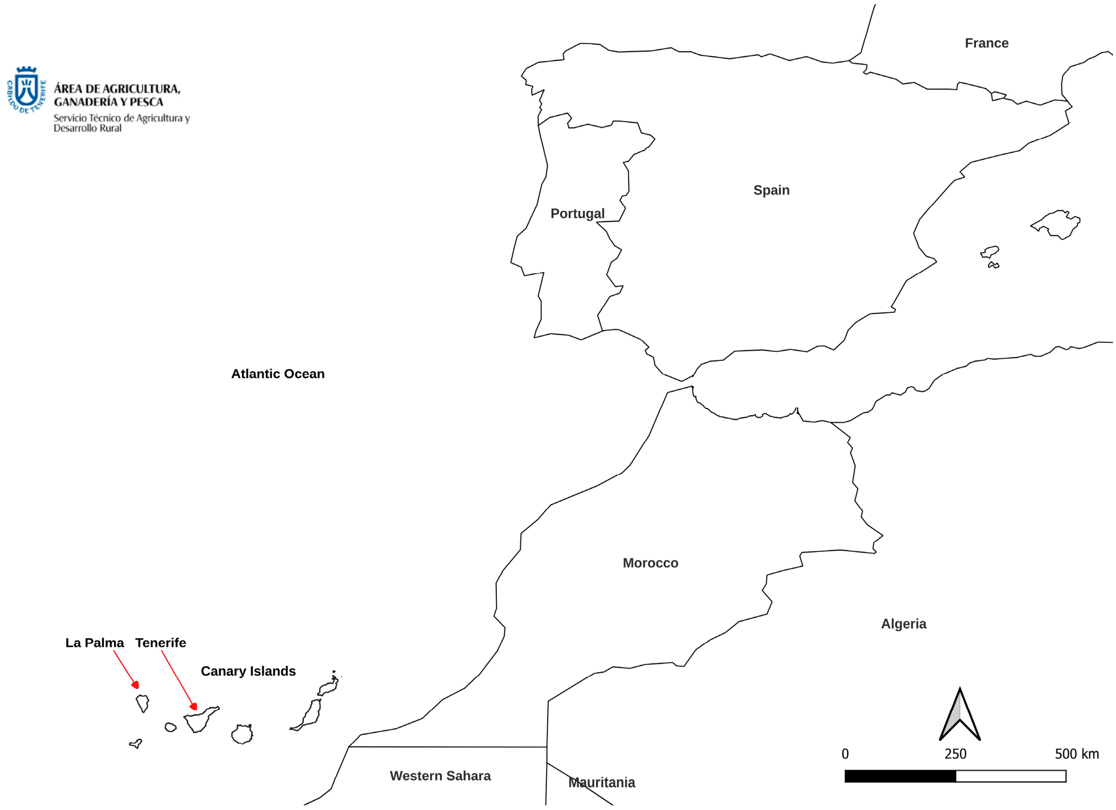


Figure 1. Localization of the Canary Islands.

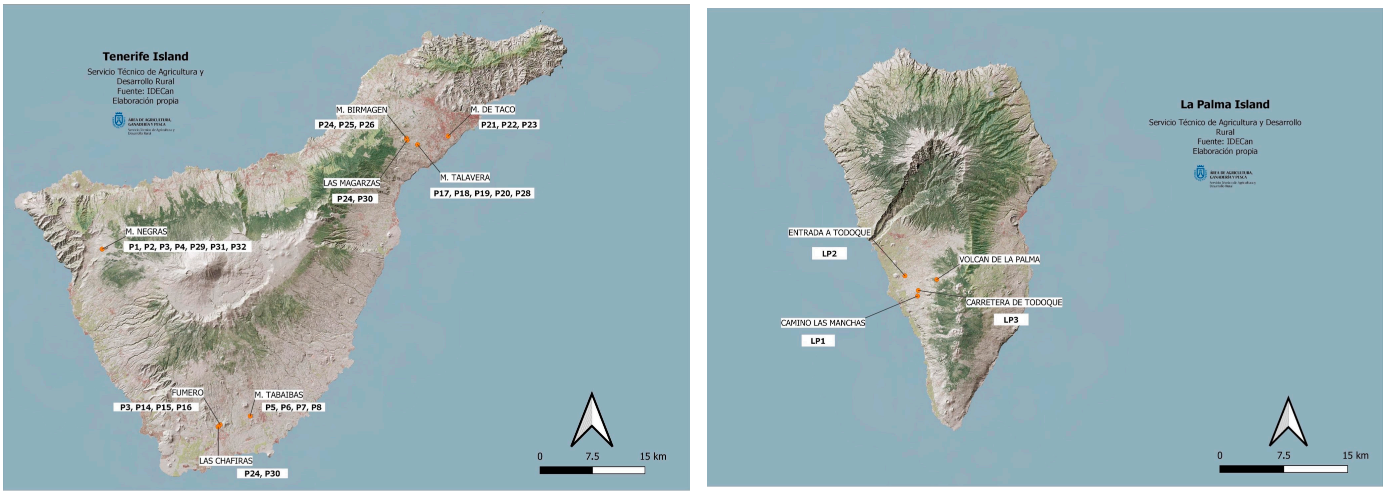
The recent eruption on the island of La Palma (Canary Islands) ejected more than 1,0 0.10^7 m^3 of pyroclastic materials [29]. An average of 150,000 m^3/day of volcanic ash is estimated to have been emitted during the 100 days that the eruption lasted [30].

The objectives of this study are to determine the main physical properties of a large set of tephras from the Canary Islands and to search for a simple method to predict their physical characteristics based on their particle size. Based on this method, a provisional forecast of the physical characteristics and their possible use as a substrate can then be made from the materials of the La Palma volcano.

2. Materials and Methods

A total of 32 samples from eight quarries in Tenerife (Canary Islands) (Figure 2a) were employed for the study. The samples were either taken from the piles prepared for transport, possibly with some prior processing (screening or crushing), or alternatively directly from the extraction zone without any manipulation. Three main types were found, defined by the quarry staff:

- Coarse tephras, normally obtained by classification through sieving and eliminating fine materials; intended mainly as aggregate for public works.
- Fine tephras or “sands”, obtained by sieving eliminating coarse materials or crushing and intended for lightweight concrete block production.
- Intermediate or “mixed up” tephras as dug from the quarry without any classification or handling process.



(**a**) (**b**)

Figure 2. Distribution of the sampled tuffs: (**a**): sampled quarries and sampled tephras in Tenerife, respectively; (**b**) sampled areas in La Palma.

The particle size distribution was determined on air-dried samples of 200 mL. A digital electromagnetic sieve shaker (Model Cisa 002) was employed, working at maximum power for 10 min. Square hole sieves of 16, 8, 4, 2, 1, 0.5, 0.25 and 0.125 mm were used, and a coarseness index (CI) defined as the cumulative percentage of particles with a diameter greater than 1 mm [4] was calculated.

Particle density was determined using water pycnometry [31] while obtaining the effective porosity (Pe) in an unaltered sample and the total pore space (TPS) in a pulverised sample. The occluded porosity (Pc) was then evaluated as the difference between TPS and Pe.

The water release curve was measured using the De Boodt and Verdonck method [32], taking data at 1, 2, 3, 5 and 10 kPa. With the data obtained, the curves were fitted using the Van Genuchten model [33], which has been shown to adapt well to substrates and tuffs in particular [3,27,34].

With the data obtained in the water retention curve, the following characteristics were calculated [32], always using % by volume:

Air-filled porosity (AFP) is the difference between Pe (assumed to be equal to volumetric water content at 0 kPa θ(0 kPa), whereby θ is defined as the volumetric water content) and θ(1 kPa).

Easily available water (EAW) is the water content released when suction rises from 1 to 5 kPa, so (θ(1 kPa)–θ(5 kPa)).

Water buffet capacity (WBC) is the water content released by raising suction from 5 to 10 kPa, so (θ(5 kPa)–θ(10 kPa)).

In this study, available water (AW) is defined as the sum of easily available water plus the reserve water: AW = EAW + WBC.

Unavailable water (UW) is the volumetric content of water at 10 kPa.

All studies were performed in triplicate, whereby the fit of the water release curves to the Van Genuchten model was performed via nonlinear equations. A statistical correlation analysis (Pearson's r correlation coefficient) between the determined air–water ratios and the particle size distribution was performed (Table 1). Lastly, regression equations between the CI and some air–water relations were adjusted to explore the possibility that this parameter may be used to predict the physical behaviour of the tuffs. In all 3 cases, the SPSS software was used.

Table 1. Mean fitted values and coefficients of determination (R). Model of Van Genuchten.

Type	θ_s	θ_r	α	n	R
Coarse	53.5	3.778	0.0042	1.308	0.994
Intermediate	46.7	5.405	0.1373	1.510	0.981
Fine	50.3	2.958	0.7846	1.622	0.998

Three samples of pyroclastic materials were taken in the area south of the lava flows coming from the La Palma Volcano (Figure 2b). These samples underwent the same particle size analysis as the 32 samples from Tenerife.

3. Results and Discussion

3.1. Particle Size Distribution

Figure 3 shows the particle size distribution of the most extreme tephras of each type.

Coarse tephras: This group included materials with a CI greater than 90%. The most abundant fraction was found to be between 4 and 8 mm, with a relatively limited variety of sizes (Figure 3a,b). In the Canary Islands, coarse-type materials have mainly been used for soilless cultivation [23,25].

Fine tephras: These materials, with a CI less than 60%, are obtained either by sieving, with a higher quantity of fine materials (for samples P16 and P17, the most abundant fraction was between 0.5–1 mm (Figure 3f)), or by crushing (for P8 and P9, the most abundant fraction was between 2–4 mm (Figure 3e)). These materials are seldom used for soilless cultivation with sparse references of using fine tephras as horticultural substrates [24].

Intermediate tephras: This group was fairly heterogeneous. Half of the samples' most abundant fraction was between 2 and 4 mm, while in the others this was between 4–8 mm (Figure 3c,d). These presented a particle size deviation from the coarse and fine materials and closely resembled those used in Israel [12,13,27,28,35].

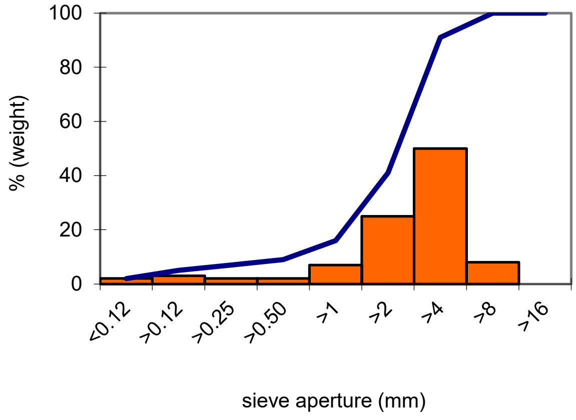
Figure 4 shows the grain-size distribution of the three samples from La Palma. They were materials with a high percentage of particles smaller than 1 mm. All three samples would clearly be classed as fine tephras. The LP2 (Figure 4b) material presented a finer grain size than the others did, with more than 40% concentrated between 0.25 and 0.125 mm. Samples LP1 (Figure 4a) and LP3 (Figure 4c) had particle size distributions similar to those obtained by sieving in the Tenerife quarries and demonstrated a highly dispersed particle size (Figure 2e).

3.2. Air–Water Relations

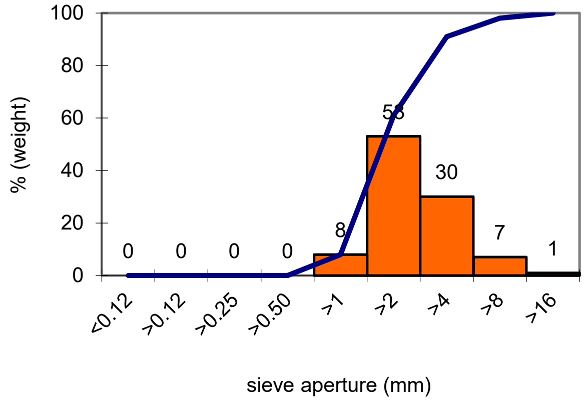
Table 2 illustrates the main air–water ratios of the tephras investigated, while Table 1 and Figure 5 show the mean fitted values and water retention curves of the three groups.

Coarse tephras: These materials presented a high aeration capacity (30–50%) and low water retention (with an AW: 2–5%). A very pronounced drop in water content was observed from saturation, where practically all the available water was released at suctions below 2 kPa (Figure 5). The results describing the physical characteristics are comparable to the literature, both in the Canary Islands [10] and to that of other basaltic materials of similar size of Catalonia [26] and México [16,36] (Table 3).

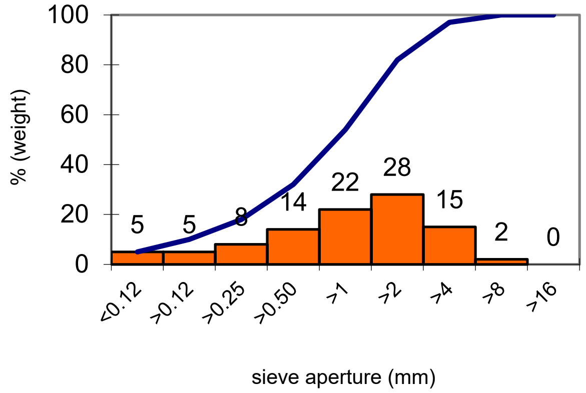
Fine tuffs: This group presented a lower aeration capacity than coarse materials (10–30%) and a better water storage capacity (AW 20–26%). A zone of low gradient at very low suction was observed in the fitted retention curves (Figure 5); much like a perlite, this showed a gradual water release throughout the water retention curve [35].



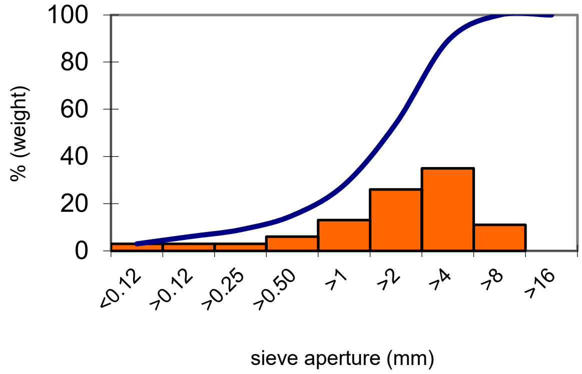
(**a**) P12 (CI = 90%)



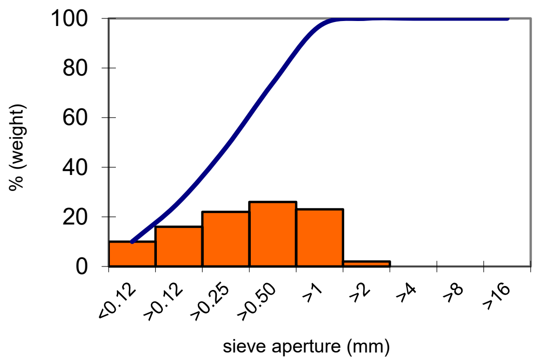
(**b**) P2 (CI = 100%)



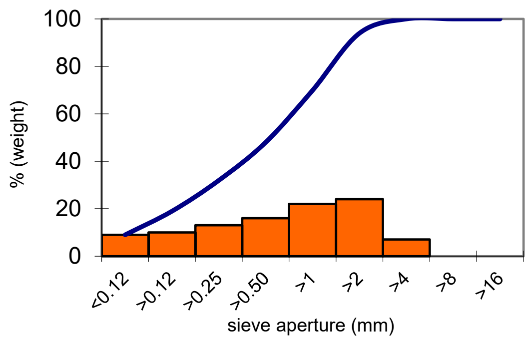
(**c**) P25 (CI = 66%)



(**d**) P29 (CI = 85%)

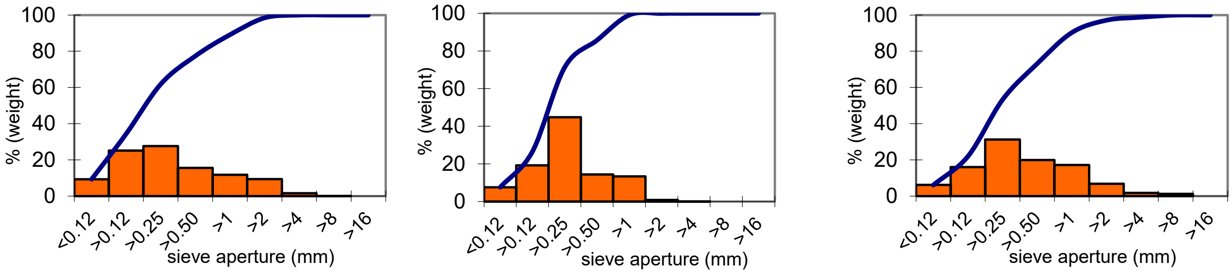


(**e**) P17 (CI = 26%)



(**f**) P9 (CI = 55%)

Figure 3. Grain-size distribution of the materials with smallest and largest CI from each category: (**a**,**b**) coarse tephras; (**c**,**d**) intermediate tephras and (**e**,**f**) fine tephras.



(**a**) LP1 (CI = 23%) (**b**) LP2 (CI = 14%) (**c**) LP3 (CI = 27%)

Figure 4. Grain-size distribution of the 3 samples collected in La Palma.

Table 2. Air–water relations for the tephras analysed (arranged in descending CI).

Sample	CI	Pe	AFP	EAW	WBC	UW
	% (Weight)	% (Vol.)	% (Vol.)			
			Coarse Tephras			
P2	100	50.0	38.7	1.50	0.22	9.61
P32	99	57.7	48.1	2.58	0.63	6.47
P13	98	52.0	39.2	4.13	0.90	7.71
P14	98	52.5	40.3	3.03	0.55	8.63
P18	98	60.8	49.0	2.48	0.77	7.65
P27	97	52.0	37.8	2.79	0.46	10.93
P19	95	53.3	36.5	5.31	1.99	9.53
P15	94	50.4	39.8	3.95	1.05	5.54
P5	93	52.5	52.2	2.82	0.40	8.21
P7	93	63.7	39.9	4.42	0.74	9.26
P1	93	54.3	43.4	0.64	0.14	8.27
P4	92	56.9	45.8	3.35	0.83	6.02
P31	92	52.5	43.0	2.28	0.51	6.74
P3	90	55.3	44.8	3.84	0.96	5.69
P12	90	48.3	37.6	2.66	0.69	7.36
			Intermediate tephras			
P29	85	47.6	30.5	6.24	1.80	8.26
P20	82	46.0	25.1	12.71	1.57	6.30
P10	80	43.5	28.9	3.89	1.22	9.57
P30	80	39.7	11.8	14.32	2.28	11.30
P26	78	47.9	28.2	6.82	0.89	13.42
P21	76	50.4	41.1	2.59	0.55	6.22
P28	75	45.0	23.7	7.04	2.36	11.90
P6	74	45.4	24.7	4.58	0.78	15.62
P23	74	50.7	32.7	8.79	1.02	9.17
P24	74	46.3	25.8	8.55	1.38	10.86
P22	73	46.5	29.9	5.80	1.21	9.56
P11	71	52.3	37.9	5.69	0.89	8.05
P25	66	49.0	32.1	7.90	1.45	7.59
			Fine tephras			
P8	53	41.7	29.9	11.65	2.25	13.89
P9	55	54.4	10.3	16.12	4.32	13.82
P16	30	55.7	19.5	20.96	5.16	9.86
P17	26	49.5	12.1	21.21	3.05	13.14

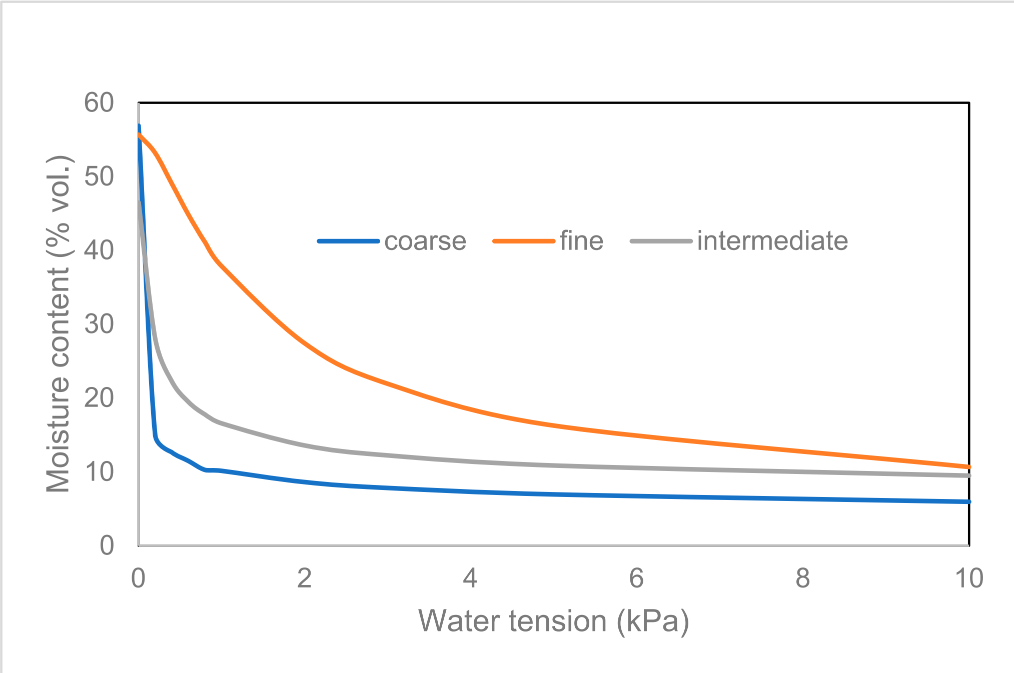


Figure 5. Mean fitted water retention curves of the three tephra types.

Table 3. Mean air–water relations of three tephra groups compared with other volcanic materials mm [6,27,36].

Type	Pe	AFP	EAW	WBC
	% (Vol.)			
Coarse	54.1	43.0	3.1	0.7
Intermediate	47.0	28.6	7.3	1.3
Fine	50.0	17.9	17.5	3.7
Red tuff (RTB) 0–8 mm [27]	58.7	38.7	7.5	1.3
Tezontle 0–3 mm [36].	56.6	44.4	2.9	7.8
Pumice 0–8 mm [6]	53.0	19.7	4.8	1.5

Intermediate tuffs: Once again, this group was the most heterogeneous, with intermediate characteristics between the fine and coarse materials, an aeration capacity between 20 and 35% and available water between 5 and 15%. The intermediate tuffs presented similar behaviour to the coarse tuffs, but with an asymptotic zone that began at 3–4 kPa (Figure 5). Materials described by [27,28,35] from Israel would fall within this group (Table 3).

Based on the previous results, the coarse-type material substrates used in the Canary Islands [23,25] would have a low water retention capacity that would make irrigation management difficult, especially when the material is not colonised by roots, which help to decrease the actual pore size [1]. With respect to the air–water ratios, it may be more recommendable to employ materials of smaller grain that are of an intermediate or even finer type, and which have a good AFP with greater available water than the coarse materials used up to now. Tephras have air–water relations more like other substrates used [12,27], better than other volcanic materials such as pumice [6] (Table 3).

Figure 6 shows the mean air–water relations (AFP, EAW, WBC and Pc) for each type of tuff. The importance of occluded porosity in these materials should be noted: occluded porosity can influence the relationship between particle size distribution and air–water ratios [35,37].

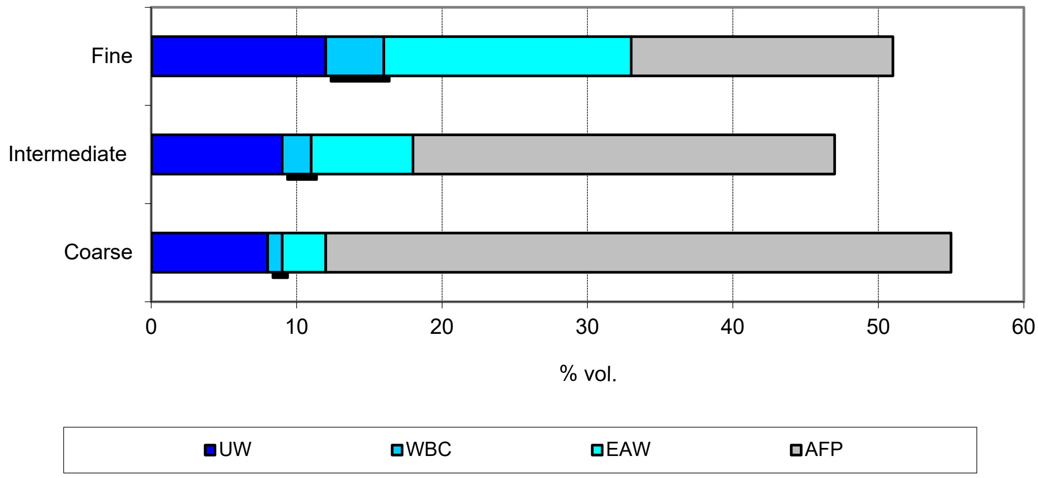


Figure 6. Mean overall porosity of the three groups.

3.3. Correlations between Granulometry and Air–Water Relations

In general, there was a clear inverse relation between particle size and water retention (Table 4). Particles larger than 8 mm did not demonstrate any significant correlation with either the aeration or any of the properties related to water retention. Particles between 2 and 8 mm correlated significantly negatively with water retention and positively with aeration.

Table 4. Correlation matrix between granulometry and the air–water relations of tuffs analysed.

Property	CI	Grain Fractions								
		>16	16–8	8–4	4–2	2–0.1	1–0.5	0.5–0.25	0.25–0.125	<0.125
	Pearson's "r" Coefficient									
AFP	0.762	0.054	0.105	0.546	0.589	−0.366	−0.676	−0.749	−0.755	−0.762
EAW	−0.881	−0.067	−0.252	−0.701	−0.521	0.470	0.812	0.885	0.858	0.767
WBC	−0.799	−0.123	−0.256	−0.627	−0.401	0.354	0.661	0.809	0.811	0.782
AW	−0.880	−0.077	−0.256	−0.703	−0.506	0.457	0.799	0.886	0.863	0.783
UW	−0.487	−0.070	−0.113	−0.323	−0.315	0.136	0.378	0.502	0.551	0.564

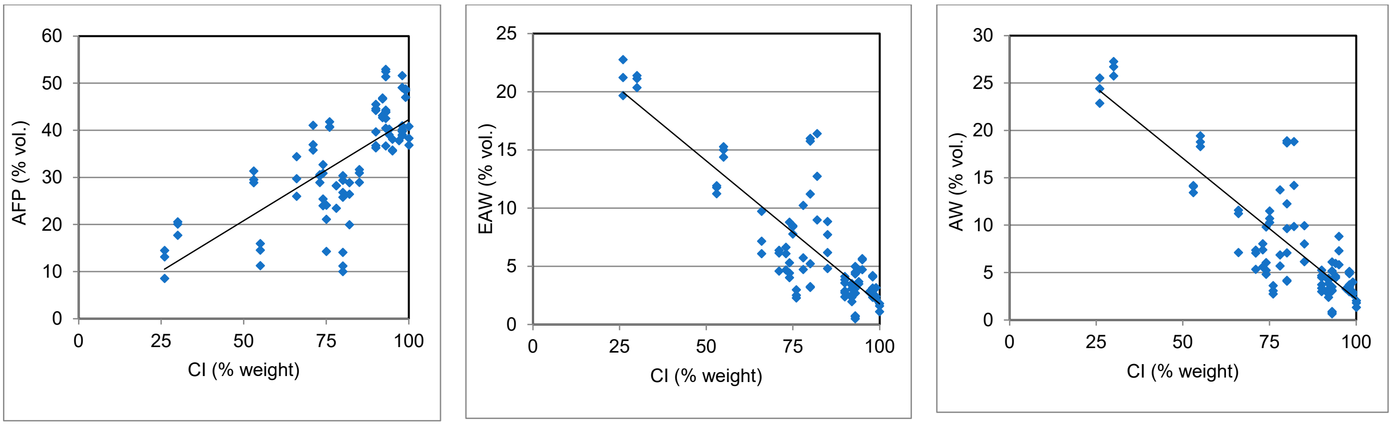
For significant correlations: $r > 0.449$ ($p = 0.01$).

Particles smaller than 2 mm and especially those below 1 mm displayed a highly positive correlation with water retention, which has been observed for organic substrates [4], tuffs and tezontles [16,28,37]. Both AFD and AR correlated especially well with particles between 0.5 and 0.125 mm. A particle size less than 0.5 mm has been shown to demonstrate a highly significant change in the physical properties of coconut fibres [38].

While taking these correlations into account, CI was chosen to aid the air–water ratio predictions of a given tephra. The AFP, EAW and AW were specifically evaluated using linear regression (Figure 7). In other materials, linear regression equations have also been used successfully to predict some parameters for air–water relations [36,37]. The coarseness index was used as it is a fast and simple parameter to determine.

The linear regression equations obtained are as follows:

- AFP = 0.4288 CI–0.6013; R= 0.523 ($p > 0.001$).
- EAW = 26.350–0.246 CI; R= 0.723 ($p > 0.001$).
- AW = 31.899–0.297 CI; R=0.728 ($p > 0.001$).



(**a**) (**b**) (**c**)

Figure 7. Linear regression: (**a**) AFP: CI; (**b**) EAW: CI; (**c**) AW: CI.

3.4. Air–Water Estimates for the Materials Recovered at La Palma

The approximate values of the air–water relations for the three samples collected in La Palma were estimated based on the previous relations (Table 5). Of the calculated air–water ratios, the predicted AFP value would be the most limiting factor, with values lower than 10% for LP1 and LP2, values indicated by [39] as the lower limit for tomato cultivation with most media and mixes having an AFP of 10–30% [1].

Table 5. Predicted air–water relations for the material collected in La Palma.

Sample	CI	AFP	EAW	AW
	% (Weight)	% (Vol.)		
LP1	23	9.3	20.7	25.1
LP2	15	5.9	22.7	27.4
LP3	27	11.0	19.7	23.9

Taking into account that the height of the container will influence the effect of AFP on root growth [4,34,40], using a substrate of greater height than with coarser tuff, and thus going to 20 cm, could allow LP3 and LP1 to be used as substrates for growing horticultural crops [17,39].

4. Conclusions

The tephras had hydraulic properties that were highly influenced by the particle size. Coarse tuffs had an aeration capacity greater than 35% v/v and easily available water of less than 5% (v/v), while fine tuffs had aeration capacities below 20% v/v and elevated water retention (20 to 26% v/v). The intermediate tephras had characteristics that varied between those of the two previous groups. Particle size fractions of less than 1 mm demonstrated the best correlation to common air:water ratios and present the best predictive capacity to relations involving air.

Based on the obtained results, it appears to be recommendable to use materials that are finer than those usually employed until now. Intermediate or fine tephras had air–water relations that enable a simpler management of irrigation.

The use of linear regression equations, which allow for an approximate prediction of air–water relations based on the coarseness index, can help to manage the picon in issues such as the height of the substrate in the container or in irrigation control. According to parameters predetermined through equations that were developed for picones from Tenerife, the materials that were sampled in La Palma can be used as substrates in horticultural cultivation, taking into account their lower aeration capacity.

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