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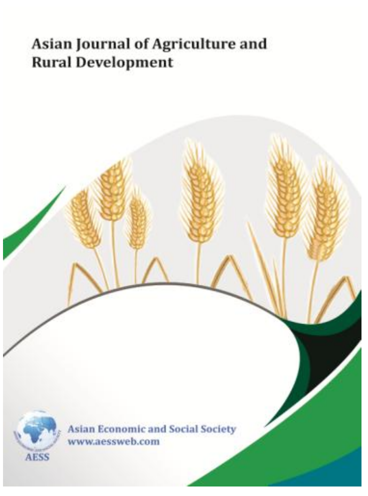

Exploring the Influence of Coal Rubble and Pine Bark Substrate Mixes on Germination, Spiral Rooting, Substrate Chemical and Physical Properties: Using Tobacco as Test Crop

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Exploring the Influence of Coal Rubble and Pine Bark Substrate Mixes on Germination, Spiral Rooting, Substrate Chemical and Physical Properties: Using Tobacco as Test Crop

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Abstract

A study was carried out under greenhouse conditions to establish the role of substrate physical and chemical properties. Pine bark and coal rubble were mixed at 100, 75, 50, 25, and 0% by volume. A farmers' standard practice (50% pine bark + 50% sand) was included as a control. The experiment was made up of three blocks and six treatments arranged in a randomized complete block design. The particle density of the substrates in this study was virtually the same. The bulk density, total porosity, and aeration porosity, however, were highest with 100% coal rubble and decreased with decreasing coal rubble proportion while water holding porosity increased with decreasing coal proportion. Germination decreased with increasing coal rubble at 14 to 28 and at 35 days after sowing (DAS). A mix of between 0 to 50% coal rubble with pine bark seemed ideal for germination. Aeration porosity, total porosity, and bulk density were negatively correlated to germination (14 to 28 DAS) while water holding porosity was positively correlated. Overall, the best germination was for 0 to 50 % coal rubble with subsequent bulky density of 0.46 to 0.83, total porosity 71 to 63%, aeration porosity 21 to 35% and water holding porosity 49 to 31% respectively. However, the measured total porosity and water holding porosity of the standard substrate (50%S0%CR50%PB) used normally by farmers were below the expected range, while the aeration porosity was on the low end. This makes this mix prone to aeration problems. The pH of the float water decreased with increase in time from sowing and proportion of coal in the mix while EC was not affected.

Keywords: Total Porosity, Aeration Porosity, Electrical Conductivity, Germination, pH

Introduction

Essentially, the profitability of soilless grown crops is higher than of those grown in soil mainly because soilless substrates are superior in physical and chemical properties, have a low infestation with pests and are easier to disinfest between growing cycles (Raviv *et al*., 2002).

Although genetics plays a role, good plant development depends to a marked degree on the physical (bulk density, porosity, water-holding capacity and plasticity) and chemical (buffer capacity, fertility and acidity) properties of the growing substrate. A good root system will always mean that the plant will be able to withstand harsh growing conditions. A good substrate must be light, firm, retain enough moisture, be porous, aerated, be free from pests, be biostable, low in salinity, suitable pH, and be stable and not expand, shrink or crust over excessively.

Bulky density, a substrate's dry mass per unit volume (in a moist state in g cm^{-3}), affects stability in potted plants. In this case a high bulky density is important while greenhouse production requires low bulky density (Raviv *et* *al*., 2002). The floating system thus would require low bulky density substrates as high ones could mean the floating trays would sink too deep in the pond, leading to water logging. The 50% pine bark: 50 % sand mix which is the current farmer's choice in Zimbabwe is based on this reasoning (Mazarura & Asher, 2011).

A substrate that can hold a large amount of water without water logging will need reduced irrigation frequency. The container also affects the water holding capacity of a substrate, with higher water holding capacity being associated with shallow containers than deep ones. Thus water holding capacity is not likely to be a limiting factor under the floating tray (FT) system as the trays that are used are shallow (5 cm) and as long as a substrate with good wicking is chosen.

The total porosity or total pore space is made up of the sum of the gaseous (air) and liquid (water) phase, technically termed water holding porosity and the air filled porosity (Raviv *et al*., 2002). The size and size distribution, shape, and arrangement of a substrate's particles will have a marked effect on total porosity. A good porosity means sufficient oxygen will be available to the roots, preventing rotting. Carbon dioxide from respiration must be taken away from the root zone quickly. It is accepted that less than 12% oxygen in the root system would make plants fail to produce new roots and between 5 to 10% roots would stop growing and below 3% they would die. To maintain oxygen above 12% a porosity of 50-80% by volume is ideal in container plants. In the float system, such high figures are not very common with pine bark because of the overriding effect of a shallow cell.

Shrinking and cracking when drying will almost certainly damage roots. Such plasticity is seldom apparent in floating tray system substrates. A low bulk density is ideal under the FT system as this means a tray would float higher, thereby creating conditions for higher porosity.

The normal ranges for total porosity are 50-85%, aeration porosity 10-30%, water holding porosity (container capacity) 45-65% and bulky density 0.19 to 52 g/cc (Breedlove *et al*. 1999). These factors have marked effect on germination and plant growth. Masaka *et al*. (2007), however, could not clearly relate aeration and water holding porosity to the variation in germination they observed. Masaka & Ndidzano (2008) observed decreasing germination at 35DAS as the amount of coal rubble increased in a coal/pine bark substrate mix, presumably because of decreasing water holding porosity (Masaka *et al*., 2007).

Chemically, the substrate must be able to release N, P, K and other macro and micronutrients to the growing plant. The pH must usually be between 5.5 and 6.5 for most plants, outside this range some nutrients would be immobile while others would exhibit toxicity. The cation exchange capacity (CEC) or fertiliser storage capacity is a measure of how a substrate is able to adsorb charged ions. The common of such cations would be calcium, magnesium, potassium, ammonium listed with decreasing capacity to be adsorbed. The substrate will store these until they are made available to the growing plant. Too strong adsorption would fix nutrients and make them unavailable to plants. Some soil-less substrates have high CEC but anions get lost easily requiring frequent replenishing. For pine bark the loss of P can be significant since the bark "micells' are negatively charged while P is also negatively charged.

Soil less substrate is a convenient replacement for soil based substrates because materials used have, when mixed in the right quantities, optimal chemical and physical properties, contain no weed seeds, insects, pathogens and are biostable even under heat sterilisation. These materials are admixtures of inorganic (polystyrene, vermiculite, perlite, gravel, sand, pumice, and tuff) and organic (charcoal, peat, hardwood and softwood barks, rice hulls, compost, sawdust and other organic farm waste products) alone or in various combinations.

Successful seedling production in the floating tray system described by Mazarura & Asher (2011) or even nursery seedling production depends to a large extent on the physical and chemical properties of the substrate used. A good substrate must bring water and air to the plant, provide anchorage and maintain biostability during the important time course of the emergence and early or later establishment of a seedling. Often, this cannot be achieved by a single substrate; hence, the practice of mixing various proportions of a number of substrates in order to achieve the necessary chemical and physical properties.

When roots initially grow into the air instead of into the ground, the phenomenon is called spiral rooting. The exact cause of this is not known, but certainly many factors like crop variety and pellet type (Fisher 2011), seed covering and priming (Peek *et al*., 2011;Smith *et al*., 2000), particle size distribution (Masaka *et al*., 2007), too much water or too little air (Peek *et al*., 2011), tray depth, shallower trays having higher spiralling (Bailey *et al*., 2012) and many other factors.

The aim of this study was to determine the physical and chemical properties of different substrate mixes and study the response of a model crop to various substrate mixes of pine bark, coal rubble and sand.

Materials and Methods

Site and Substrate Preparation

The experiment was carried out at the Tobacco Research Board, Zimbabwe (17^0 55` S, $31^0$ 08`, Harare, about 1500 meters above sea level). Coal rubble was crushed and passed through a 4mm sieve. Finer particles were removed by passing through a 1mm sieve to remain with particle-sized between 1mm to 4mm, which were then thoroughly washed with tap water. The coal rubble and pine bark were mixed in the desired proportions. For the pine bark the particle size distribution was 20% for particles less than 1mm, 70% for particles greater than 1mm but less than 4mm and 10% for particles above 4mm but below 6mm in diameter. The six treatments derived from the constituent substrates were as follows (note codes in brackets):

1 0% sand +100% coal rubble + 0% pine bark (0%S100%CR0%PB)
2 0% sand + 75% coal rubble + 25% pine bark (0%S100%CR25%PB)
3 0% sand + 50% coal rubble + 50% pine bark (0%S50%CR50%PB)
4 0% sand + 25% coal rubble + 75% pine bark (0%S25%CR75%PB)
5 0% sand + 0% coal rubble + 100% pine bark (0%S0%CR100%PB)
6 50% sand + 0% coal rubble + 50% pine bark (50%S0%CR50%PB)

Measurement of Physical and Chemical Properties

From each treatment two composite samples were collected and one was chemically analysed while the physical characteristic of the other were determined. The physical characteristics which were determined included the bulk density, particle density, total porosity, aeration porosity and water holding porosity (Masaka *et al*., 2007). The remainder of the substrate for each treatment was used to establish tobacco float seedlings according to Mazarura & Asher (2011). The initial EC and pH readings of the water in the float bed were taken before floating and thereafter at 7, 14, 21, 28 and 35 days after fertilizer application. Basal fertilizer application was done at 4 day after sowing (DAS) with a soluble (20%N: 10% P_2O_5: 20% K_20) fertilizer at 150mgN/L and top dressing was then done at 42 days after sowing (DAS) with Ammonium Nitrate (34.5% N: 0% P_2O_5: 0%K_2O) at 150mgN/L.

Experimental Design and Experimental Handling

The experiment was a randomized complete block of three blocks each with six treatments. The variety KRK26 was used for this study. The floating depth of trays at floating, germination and spiral root count at 14, 21, 28 and 35DAS were taken from the middle 50 cells of the centre of three trays per treatment. The experiment utilized 200 cell trays in greenhouse float beds. All data were subjected to ANOVA using Genstat Version 11.0. Mean separation was conducted using Fischer's Protected Least Significant Difference (LSD) test at P<0.05.

Results

Substrate Physical Properties

With regard to particle density the six substrate mixes were essentially the same. However, in terms of bulk density the substrate could be arranged in the order 0%S100%CR0%PB and 50%S0%CR50%PB > 0%S100%CR25%PB > 0%S50%CR50%PB > 0%S25%CR75%PB > 0%S0%CR100%PB (Table 1). Based on total porosity, the 100% coal rubble had the highest while the 50%S0%CR50%PB had significantly (P<0.05) the least (Table 1). The other mixes with pine bark exhibited values in between these two extremes. The control treatment had the lowest total porosity and aeration porosity and one of the lowest water holding porosity. The 100% coal rubble also exhibited the highest aeration porosity while the various mixes showed the influence of coal ruble as it was reduced to 25% of the mix. Water holding porosity was, however, largest with the 100% pine bark substrate and reduced with reducing amount of pine bark in subsequent mixes. Water holding porosity was negatively correlated with bulk density (r= -0.953, p=0.049). In terms of height of floatation and wicking time the mixes were not different from each other (p>0.05) (Table 2).

Table 1: The Physical Properties of Sand, Pine Bark and Coal Rubble Substrate Mixes

Treatment	Particle density	Bulk density	Total porosity	Aeration porosity	Water holding porosity
0%S100%CR0%PB	0.98a	1.04e	75.6d	55.6f	19.9a
0%S75%CR25%PB	0.96a	0.92d	64.8b	40.7e	24.1ab
0%S50%CR50%PB	0.96a	0.83c	63.9b	32.5d	31.5b
0%S25%CR75%PB	0.98a	0.68b	69.9c	24.5c	45.4c
0%S0%CR100%PB	0.95a	0.46a	71.0c	21.1ac	49.8c
50%S0%CR50%PB	1.03a	1.01e	43.6a	16.1a	27.5a

Means followed by different letters are significantly different at P=0.001

Table 2: The Height of Floatation and Wicking Time of Sand, Pine Bark and Coal Rubble Substrate Mixes

Treatment	Height of floatation	Wicking time
0%S100%CR0%PB	330a	106.7a
0%S100%CR25%PB	563a	109.7a
0%S50%CR50%PB	236a	110.7a
0%S25%CR75%PB	462a	106.7a
0%S0%CR100%PB	286a	107.0a
50%S0%CR50%PB	350a	109.0a

Means followed by different letters are significantly different at P=0.001

A plot of bulk density against the proportion of coal rubble showed that the bulk density increased with increasing amount of coal rubble and the relationship was quadratic (Fig. 1). Aeration porosity was similarly related to increasing coal amount (Fig. 2) while water holding porosity declined with increasing coal proportion (Fig. 3) and total porosity declined initially as the proportion of coal ruble increased down to 60% after which it began to rise (Fig 4).

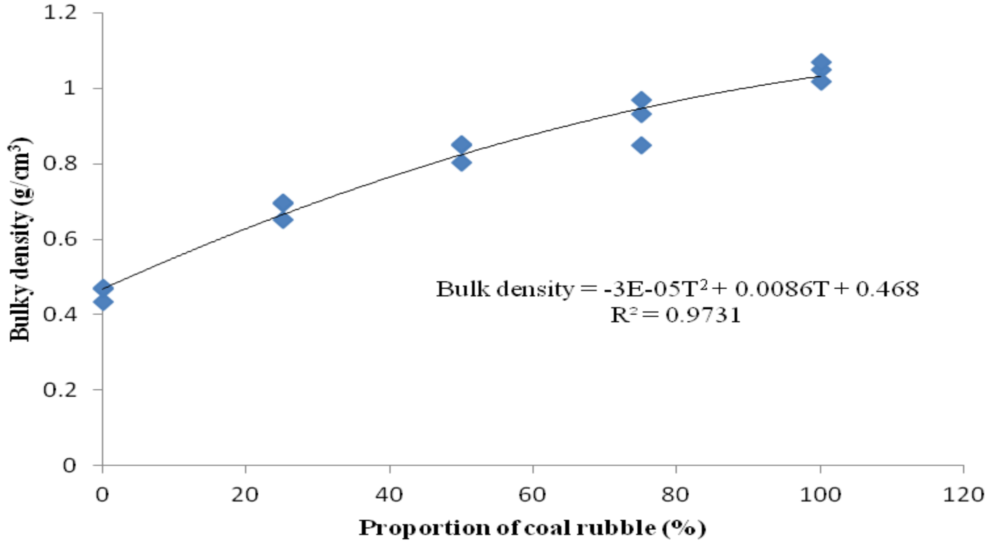

Figure 1: The Relationship between Bulky Density and The Proportion of Coal Rubble (T) in a Pine Bark Coal Rubble Mix in which the Pine Bark Proportion is the Inverse of the Coal Proportion.

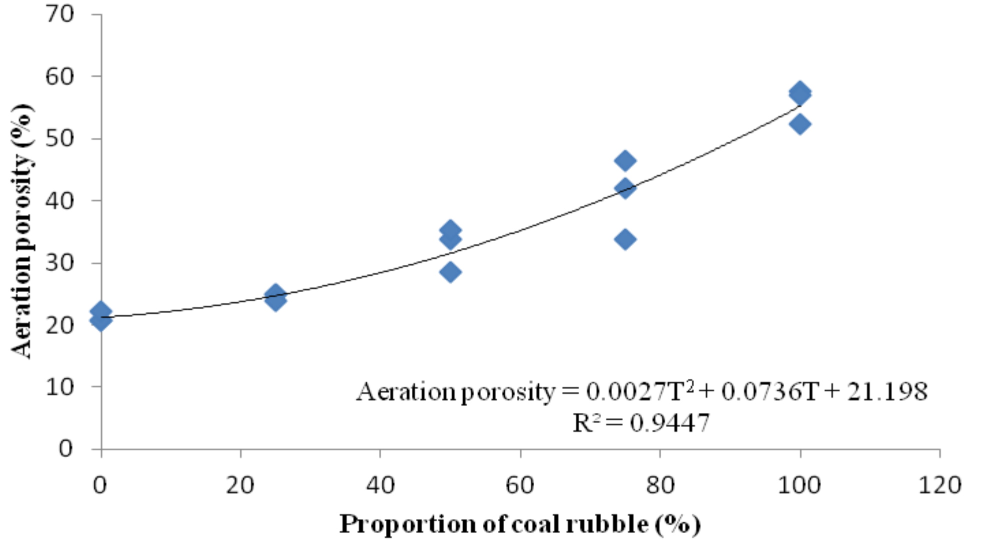

Figure 2: The Relationship between Aeration Porosity and the Proportion of Coal Rubble (T) in a Pine Bark Coal Rubble Mix in which the Pine Bark Proportion is the Inverse of the Coal Proportion

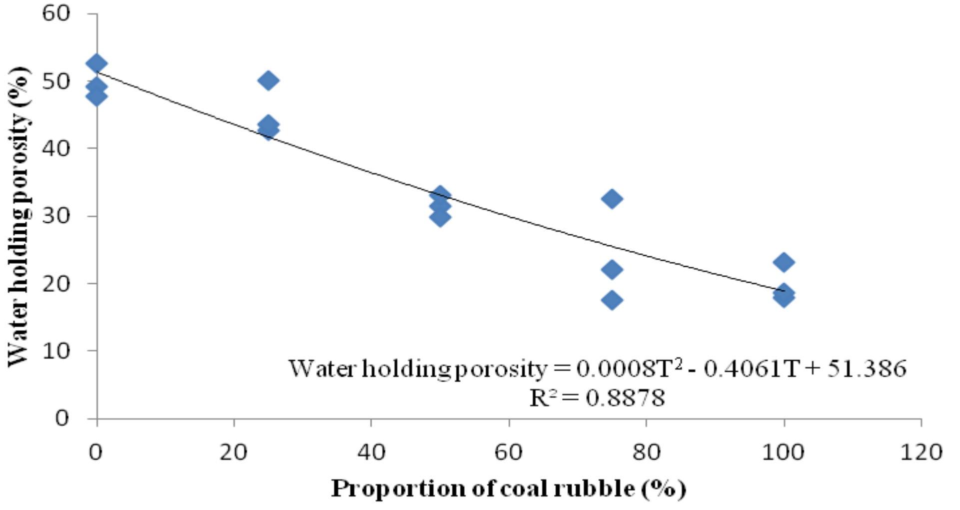

Figure 3: The Relationship between Water Holding Porosity and the Proportion of Coal Rubble (T) in a Pine Bark Coal Rubble Mix in which the Pine Bark Proportion is the Inverse of the Coal Proportion

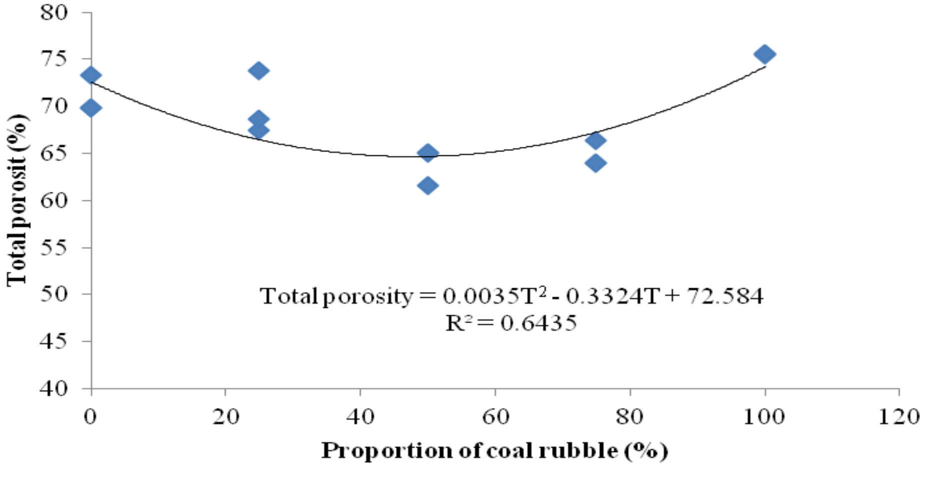

Figure 4: The Relationship between Total Porosity and the Proportion of Coal Rubble (T) in a Pine Bark Coal Rubble Mix in which the Pine Bark Proportion is the Inverse of the Coal Proportion

Substrate Chemical Properties

At the start of the experiment all testaments showed pH that ranged from neutral to basic but tended to acidify with time (Fig. 5). Fertilization at 7, 21 and 35 DAS appeared to increase pH somewhat but the decreasing trend was maintained throughout the period of the experiment. An analysis of the effect of coal rubble proportion for each sampling date showed an increasing acidity with decreasing coal proportion (Fig. 6). There was no treatment difference with regard to EC at each measurement date but the EC fell with time to half its initial value at 7 DAS by 42 DAS (Table 2).

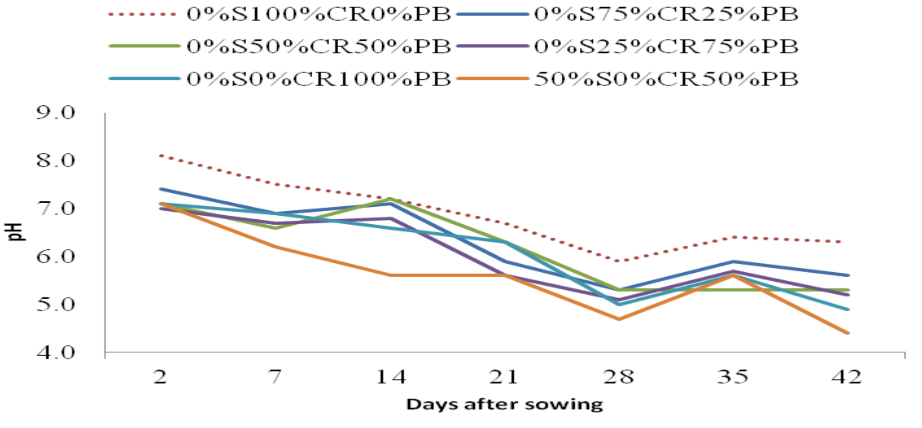

Figure 5: The Relationship between pH and Days after Sowing of Various Coal Rubble and Pine Bark Mixes

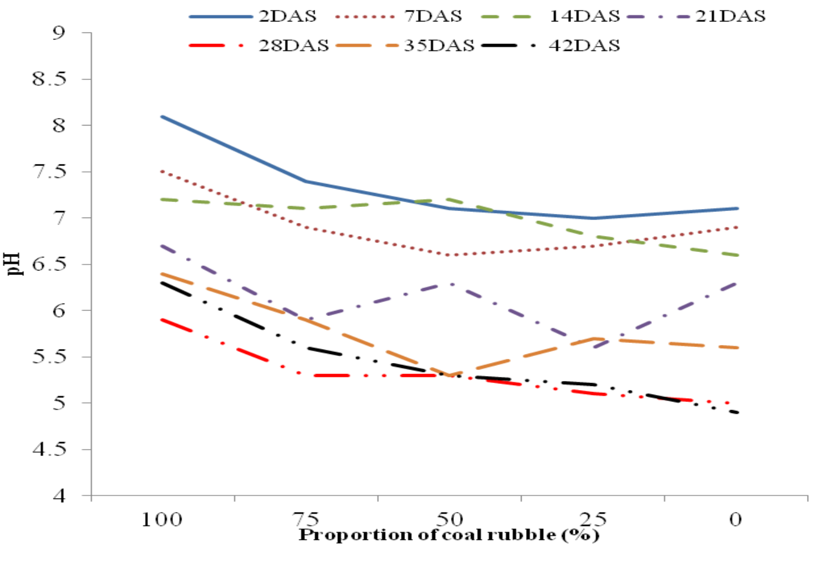

Figure 6: The Relationship between pH and the Coal Rubble Proportion in a Coal Rubble Pine Bark Mix

Table 2: The EC of Substrate Mixes from 7 to 42 Days after Sowing

Treatment	Time in days after sowing (DAS)					
	7	14	21	28	35	42
0%S100%CR0%PB	1.6a	1.3a	1.2a	1.2a	0.8a	0.8a
0%S75%CR25%PB	1.5a	1.3a	1.1a	1.0a	0.6a	0.7a
0%S50%CR50%PB	1.6a	1.3a	1.1a	1.0a	0.7a	0.6a
0%S25%CR75%PB	1.5a	1.2a	1.0a	1.0a	0.7a	0.7a
0%S0%CR100%PB	1.5a	1.2a	1.0a	0.9a	0.7a	0.7a
50%S0%CR50%PB	1.5a	1.2a	1.1a	1.1a	0.8a	0.7a

Means followed by different letters are significantly different at P=0.001

Effect of Substrate on Germination

At 14 days after sowing the substrates could be divided into two distinct groups, with substrates with 100% coal rubble showing lower germination while those with 100% to 50% pine bark showed improved germination (Table 5). This trend is evident at 21 and 28 days after sowing too. At 35 days after sowing there were no differences between the various substrates with regard to germination.

Table 3: The Germination Count for Each Treatment from 14 to 35 Days after Sowing

Treatment	Time in days after sowing (DAS)			
	14	21	28	35
0%S100%CR0%PB	70.3a	55.0a	49.0a	95.0a
0%S75%CR25%PB	108.3b	93.7b	82.3b	125.0a
0%S50%CR50%PB	142.3bc	136.0c	130.3c	130.7a
0%S25%CR75%PB	143.7c	148.0c	128.7c	67.7a
0%S0%CR100%PB	144.0c	157.3c	135.0c	87.7a
50%S0%CR50%PB	120.3c	128.0c	126.3c	125.0a

Means followed by different letters are significantly different at P=0.001

The correlation coefficients of selected parameters (those significant) against date of measurement are given in Table 4. Total porosity, aeration porosity and bulk density showed significant (P<0.01) negative correlation with germination (Table 4) while water holding porosity was positively correlated (Table 4).

Table 4: The Correlation Coefficients between Selected Physical Properties and Germination

Parameter	Date	Correlation coefficient	Probability
Aeration Porosity	14	-0.8193	0.001
	21	-0.8746	0.001
	28	-0.8637	0.001

Bulky density	14	-0.6918	0.0043
	21	-0.8234	0.001
	28	-0.774	0.001
Water holding porosity	14	0.6794	0.0053
	21	0.7938	0.001
	28	0.7528	0.0012
Total porosity	14	-0.778	0.001
	21	-0.8899	0.001
	28	-0.8592	0.001

Effect of Substrate on Spiral Rooting

Spiral rooting was significantly affected by treatment from 14 to 28 DAS and not affected at 35DAS (Table 5). From 14 to 28 DAS spiral rooting increased linearly with decreasing coal rubble. At 14DAS the relationship was explained by the equation, Spiral rooting = -0.2547T + 26.4 (R^2 = 0.6554, $P<0.001$) while at 21DAS it was explained by the equation, Spiral rooting = -0.2813T + 25.267 (R^2 = 0.5404, $P<0.002$) and by the equation, Spiral rooting = -0.096T + 8.8667 (R^2 = 0.5098, $P<0.003$) for 28DAS.

Table 5: The Spiral Root for each Treatment from 14 to 35 Days after Sowing

Treatment	**Time in days after sowing (DAS)**			
	14	**21**	**28**	**35**
0%S100%CR0%PB	2.0a	0.3a	0.0a	1.00a
0%S75%CR25%PB	4.7a	1.0a	0.0a	1.33a
0%S50%CR50%PB	9.0ab	4.7ab	1.67ab	0.00a
0%S25%CR75%PB	23.0c	18.0bc	3.33ab	1.33a
0%S0%CR100%PB	24.7c	27.0c	10.33c	1.67a
50%S0%CR50%PB	12.7b	14.7abc	7.67bc	2.00a

Means followed by different letters are significantly different at P=0.001

The correlation coefficients of selected parameters (those significant) against spiral rooting are given in Table 6. Aeration porosity and bulk density showed significant ($P<0.01$) negative correlation with spiral rooting (Table 6) while water holding porosity was positively correlated (Table 6).

Table 6: The Correlation Coefficients between Selected Physical Properties and Spiral Rooting

Parameter	Date	Correlation Coefficient	Probability
Aeration Porosity	14	-0.7411	0.0016
	21	-0.6415	0.0099
	28	-0.585	0.022
Bulky density	14	-0.814	0.001
	21	-0.75	0.0012
	28	-0.74	0.0014
Water holding porosity	14	0.7967	0.001
	21	0.7381	0.0017
	28	0.6792	0.005
Total porosity	14	-0.8096	0.001
	21	-0.7351	0.0018
	28	-0.714	0.0028

Discussion

Germination and Substrate Physical and Chemical Properties

In general a good substrate must be able to anchor plants firmly in place, hold enough moisture so that watering is not needed too frequently, be able to drain easily but hold enough air for the roots, have low salinity, have a pH around neutral and be bio-stable among other factors. The particle density of the substrates in this study were virtually the same perhaps because the mixes were all of plant origin or had a substantial amount of organic component in the case of the 50% sand + 50% pine bark mix. The bulk density, total porosity, and aeration porosity, however, were highest with 100% coal rubble and decreased with decreasing coal rubble proportion while water holding porosity increased with decreasing coal proportion. Floating height and wicking time did not differ.

Germination decreased with increasing coal rubble at 14 to 28 DAS and responded similarly at 35DAS. This observation is corroborated by Masaka & Ndidzano 2008, whose work using trays showed a decrease in germination with increasing coal rubble proportion in a coal/pine bark mix. In this study a mix of between 0 to 50% coal rubble with pine bark seemed ideal for germination. Aeration porosity, total porosity, and bulk density were negatively correlated to germination (14 to 28 DAS) while water holding porosity was positively correlated to germination. This observation implies a role for air porosity and water holding porosity in germination and the fact that water holding porosity decreased with increasing coal rubble proportion suggests that coal depressed germination, at least in part, by its negative effect on water holding porosity. Naasz *et al*. (2009) also reported a correlation between air filled porosity and germination and suggested that most of the phytotoxicity associated with bark substrates could be related to insufficient substrate aeration. Overall, the best germination was for 0 to 50 % coal rubble with subsequent bulky density of 0.46 to 0.83, total porosity 71 to 63%, aeration porosity 21 to 35% and water holding porosity 49 to 31% respectively. It is unlikely that water holding capacity would be an issue with the FT system since the technique is hydroponic. The values mentioned above appear adequate as the normal ranges for total porosity are 50-85%, aeration porosity 10-30%, container capacity 45-65% and bulky density 0.19 to 52 g/cc (Breedlove, Ivy & Bilderback 1999). However, the measured total porosity and water holding porosity of the standard substrate (50%S0%CR50%PB) used normally by farmers were below the expected range while the aeration porosity was on the low end. This makes this mix prone to aeration problems.

The pH of the float water decreased with increase in DAS and proportion of coal in the mix while EC was not affected. Similar results were reported by Jackson & Wright 2009 with both pine bark and pine tree substrate although this was in 15 L containers.

Effect of Substrate on Spiral Rooting

An increase in coal rubble in the coal/pine bark mix drastically reduced spiral rooting. A 50 % coal rubble + 50% pine bark seemed ideal. Spiralling was negatively correlated with aeration porosity, bulk density, and total porosity while it was positively correlated with water holding porosity. The factors that affect spiral rooting are not well understood and this work suggests that, apart from unknown substrate specific parameters, aeration limitations revealed by the above correlations may play a role in this phenomenon. Certainly many factors like variety and pellet type (Fisher, 2011), seed covering and priming (Smith *et al*., 2000), particle size distribution (Masaka *et al*., 2007) and many other factors are thought to be important. Masaka *et al*. (2007) found as in the present study that increasing the proportion of pine bark resulted in higher spiral rooting. They attributed this increased spiralling to a reduction in aeration porosity. This is confirmed in the present study, were a positive correlation between total porosity and aeration porosity is revealed. Indeed the present study also reveals that an increase in water holding porosity plays some role in increasing spiral roots. Regardless, however, their results show, as those of the present study do, that an increase in coal rubble reduces spiral roots.

Summary, Conclusions and Recommendations

Essentially, the bulk density, total porosity, and aeration porosity, were highest with 100% coal rubble and decreased with decreasing coal rubble proportion while water holding porosity increased with decreasing coal proportion. Floating height and wicking time did not differ. Germination decreased with increasing coal rubble at 14 to 28 DAS and the same at 35DAS. The mix of between 0 to 50% coal rubble with pine bark seemed ideal for germination. Aeration porosity, total porosity, and bulk density were negatively correlated to germination (14 to 28 DAS) while water holding porosity was positively correlated to germination. Overall, the best germination was for 0 to 50 % coal rubble with subsequent bulky density of 0.46 to 0.83, total porosity 71 to 63%, aeration porosity 21 to 35% and water holding porosity 49 to 31% respectively. However, the measured total porosity and container capacity of the standard substrate (50%S0%CR50%PB) used normally by farmers were below the expected range while the aeration porosity was on the low end. This makes this mix prone to aeration problems. Further work must find ways of decreasing the coal induced high pH, perhaps by using a suitable acid and then evaluating the effect of the mixes on germination once more.

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