Effect of drainage layers on water retention of potting media in containers

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Abstract

Excess water retention in the potting medium is a significant problem for plants grown in containers due to the volume of saturated medium which forms above the drainage hole. Adding a layer of coarse material like gravel or sand at the bottom is a common practise among gardeners with the aim of improving drainage, but some researchers have argued that such layers will raise the saturated area and in fact worsen drainage. Two different depths and four different materials of drainage layer were tested with three different potting media to determine the water retention in the container after saturating and draining freely. For loamless organic media, almost all types of drainage layer reduced overall water retention in the container compared to controls. For loam-based media, most drainage layers had no effect on the overall water retention. Two simple models were also used to estimate the water retention in the media alone, excluding the drainage layer itself. All drainage layers reduced water retention of loamless organic media, according to both models. There was disagreement between the two models applied to loam-based media, and further study is required to determine the most accurate. Both models showed that some drainage layers with smaller particle sizes reduced water retention in loam-based media, but disagreed on the effect of drainage layers with larger particle sizes. Overall, any drainage layer was likely to reduce water retention of any medium, and almost never increased it. Thicker drainage layers were more effective than thinner layers, with the most effective substrate depending on the potting media used. A 60mm layer of coarse sand was the most universally-effective drainage layer with all potting media tested.

Keywords: soil, water-holding capacity, container growing, drainage, potting media

1 Introduction

It is widely recognised that soil in a container behaves differently from soil in the field (Hershey 1990; Landis, 1989; Spomer, 1975). One of the most significant differences is the presence of a saturated volume of soil at the bottom of the container after irrigation and draining, known as a perched water table (Bunt 1988; Goh

30 and Haynes, 1977; Handreck 2002). The depth of this saturated volume is constant for any specific soil, and
31 unaffected by container size and shape. As a result, soil in a shallower container has a greater percentage
32 water-holding capacity (WHC) than the same soil in a deeper container (Bilderback and Fonteno, 1987; Bunt,
33 1961; Hershey, 1990; Waters et al., 1970). This effect has led to the concept of container capacity, a measure
34 of the total water retained in a specific container filled with specific soil after saturation and drainage (Bunt,
35 1988; Heiskanen, 1997; Waters et al. 1970).

36 Adding a layer of rocks or gravel at the bottom of plant pots is a common practise among home gardeners,
37 as well as some researchers (Cavazza et. al. 2005), and is generally intended to reduce this perched water
38 table and improve drainage. However in recent years the recommendation has been disputed, with arguments
39 based on principles of water movement through soil suggesting that a drainage layer will in fact raise the
40 perched water table and worsen drainage overall (Chalker-Scott and Downer, 2019; Evans, 2014). Despite
41 frequent discussion of this practise, there has been little formal research into the effect drainage layers have
42 on the water-holding capacity of soil in containers.

43 A number of areas of research may be applicable to this subject in part. One of the oldest relevant studies is
44 the tests of water movement through soil interfaces conducted by Hsieh and Gardner (1959). This research
45 demonstrated that when the wetting front encounters an interface between soils of different porosities, it will
46 not advance until the soil behind is nearly saturated. Applying this to the interface between potting medium
47 and drainage substrate in a container suggests that water will not move down into the drainage layer until the
48 medium is almost saturated, and therefore the perched water table in the medium will be raised and the overall
49 aeration reduced.

50 Recent studies into the capillary break effect have similarly demonstrated that a layer of coarse material acts
51 as a barrier to water movement in field soils (Azevedo and Zornberg, 2013). Khire et al. (2000) also found
52 that more water is stored above a capillary barrier layer when it consists of coarser material than when it
53 consists of finer material. Smesrud and Selker (2001) conducted theoretical analysis which predicted that the
54 effectiveness of a capillary barrier is maximised when the contrast of particle sizes between the soil above
55 and the substrate below is infinite - in other words, when the soil is suspended over a void of air. This would
56 suggest that the perched water table created by soil over any other substrate would be less than that created
57 by soil over air.

58 Another area of recent relevant research which can be applied to this subject is the construction of green roofs,
59 which are roofs made from a layer of growing medium topped with living plants (Cascone, 2019). This shallow
60 layer of medium is surrounded by an impermeable base and sides, with a small number of drains for excess
61 water to escape through - physical conditions which are similar to a container of soil. In the construction of
62 green roofs a drainage layer of coarse substrate below the growing medium is always considered essential
63 (Berndtsson, 2010; Cascone, 2019). She and Pang (2010) found that water begins to drain out from the soil of
64 the green roof after it has reached field capacity (container capacity), but before it is fully saturated. This result

65 contrasted with predictions that water only escapes at full saturation, showing the need for further research to
66 understand the movement of water through soil in containers with layered contents.

67 Ruter (1986) found that when a fabric-bottomed container was placed on a column of sand to drain, the perched
68 water table in the medium was completely eliminated. This suggests that water moved more easily from the
69 medium to sand than from the medium into air, and therefore that adding a drainage layer of sand to the bottom
70 of a container may aid drainage. However, the column of sand in this study was many times deeper than the
71 container itself, so this may not predict the behaviour of a thin drainage layer. In addition, the fabric bottom of
72 the container may have an effect on the water movement from the medium to the sand which would not occur
73 if the two materials were in direct contact.

74 Many of the above studies were conducted on mineral field soils. In contrast, container growing often utilises
75 loamless potting media based on organic materials like peat, coir, and bark, with mineral amendments like
76 perlite and vermiculite. (Boodley and Sheldrake, 1982; Bunt, 1988; Caron et al., 2015; Evans 2014; Goh and
77 Haynes, 1977; Landis, 1989; Waters et al., 1970). These media typically have very different physical properties
78 from loams, including higher total porosity and lower water-holding capacity (Bunt and Adams, 1966; Bunt,
79 1988). As a result, the water movement through loamless media in containers may not be accurately predicted
80 by applying research conducted on field loams.

81 Further, researchers have demonstrated that the water movement and other behaviour of soil in containers is
82 highly dependent on the geometry of the container (Spomer, 1975), and can differ greatly from the behaviour
83 of even the same soil in the field (Landis, 1989). Thus, much of the research into the behaviour of water at soil
84 interfaces cannot be applied directly to the situation of container growing because it was conducted in the field
85 or in containers of very different size and shape to those generally used for live plants.

86 A typical filled plant pot consists of an impermeable container with a small number of holes in the base, full of
87 a single uniform potting medium. When the saturated medium is allowed to drain, the only interface the water
88 passes through is the drainage hole where medium meets air. In contrast, a pot with a drainage layer is a more
89 complex system. First the water passes through the interface between the medium and the drainage substrate,
90 and then it passes through the interface between the drainage substrate and the air under the drainage hole.
91 These multiple interactions make it more difficult to predict the final outcome using only theoretical analysis of
92 individual soil interfaces.

93 The effect of the volume taken up by the drainage layer is also uncertain. Assuming the same overall container
94 size, a pot with a drainage layer has a smaller volume of potting medium. Therefore, even if the percentage
95 water-holding capacity of the medium is the same in the pot with a drainage layer, the total water retained
96 at container capacity would be reduced. But instead of this reduced water retention being evenly distributed
97 through the volume of the pot (as it would be in a container filled with a more free-draining medium), it is
98 held in alternating layers of saturated and air-filled materials. The effect this would have on growing plants is
99 difficult to determine, and depends on the behaviour of roots growing towards and into the drainage layer. If

the roots do not enter the drainage layer, the plant could be considered to be effectively growing in a smaller container with the total water-holding capacity of the medium itself. However, if the roots do enter the drainage layer, they would grow through distinct layers with different moisture and air contents, as well as other physical properties.

This study aimed to determine the effect on water-holding capacity of drainage layers in containers, and compare the effect using different potting media, different drainage substrates, and different layer depths. The intention was to obtain results which could be applied by commercial nurseries and home gardeners in practice, so the conditions were chosen to closely replicate real growing containers. The study did not attempt to determine the effect of drainage layers on growing plants directly. Experiments and theoretical models were used to determine the water-holding capacity of the entire container, and of the medium alone, so that both results could be considered by readers when predicting the effects on plant growth.

2 Materials and methods

Three different types of potting media were used, as follows: JI was a loam-based John Innes No. 1 compost (Bathgate); CV was a mix of 70% coir (Coir Products Coco Peat) and 30% vermiculite (Westland Gro-Sure) by volume; CPB was a mix of 60% coir, 20% perlite (Vitax 2-6mm), and 20% pine bark (Melcourt Propagating Bark 2-7mm) by volume. The two loamless mixes were chosen to represent some of the most common loamless media used by growers according to Bunt (1988). Such media typically contain at least 50% peat or fine bark, with the remainder composed of mineral amendments (such as perlite, vermiculite, or sand), compost, or coarse bark. Coir was chosen as an acceptable alternative to peat in these mixes (Meerow, 1997; Noguera et al., 2000), due to the UK government's intention to reduce or eliminate horticultural use of peat.

Four different drainage substrates were used: gravel (Melcourt Horticultural Gravel 4-10mm), leca (LECA Lightweight Aggregate 4-10mm), grit (LECA Lightweight Aggregate 2-4mm), and sand (Dehner Aquarien Kies 1-2mm). This range of substrates was chosen to examine the influence of particle size on drainage effects, as well as to compare the effect of porous substrates with non-porous ones.

Test pots were made from clear plastic containers with a single 10mm hole cut in the centre of the base. The pots had a total capacity of 1,290ml, and were an inverted truncated cone shape with height 175mm, base diameter 86mm, top diameter 118mm, and dry weight of 53g. The base had a slight domed area raised by 4mm relative to the edges. For trials with sand, a piece of fibreglass mesh (16 x 18 mesh count, approximately 1mm spacing) was placed over the drainage hole to prevent the sand escaping. The drainage hole was temporarily sealed with tape before filling.

For each potting medium, trials were conducted with a layer of each drainage substrate to depths of 30mm and 60mm (giving a total of 24 combinations). Control trials were also conducted without drainage substrate with the pot filled with media to the top, to 30mm from the top, and to 60mm from the top. In addition, trials

133 were conducted of all the 30mm and 60mm drainage layers with no media. Ten replications were conducted
134 for each condition, with the exception of two conditions (CV-leca-30mm and sand-60mm) which each had one
135 invalid trial for a total of nine results.

136 Each potting medium was air-dried to a uniform moisture level before each condition (determined by weighing
137 a fixed volume of medium until it reached a specified mass). All the containers were then filled with equal
138 masses of medium (as recommended in the procedure Bilderback (2009) gives for measuring soil porosity in
139 the nursery) to within 5g precision. Each filled container was irrigated from above using a watering can with a
140 rose until the water level reached the top of the pot (or to the specified height for the tests involving pots filled
141 to below the top). Finally the drainage hole was unsealed and the container allowed to drain suspended on a
142 grate. Once drainage ended (which took between one minute and three hours, depending on the condition),
143 the pot was weighed a final time with its wetted contents. The mass of the empty container was subtracted from
144 the measurements to determine the initial dry mass (m_i) and drained mass (m_d) of the contents alone.

145 The saturating and draining process caused all the potting media to compact. The compacted depth was
146 measured from one representative sample for each medium with each depth of drainage substrate, and the
147 final compacted volume calculated (v). None of the drainage substrate layers compacted measurably, so their
148 final volume was taken as equal to the initial volume.

149 The water-holding capacity ($WHC = (m_d - m_i)/v$) was then calculated for each trial. ANOVA post-hoc
150 Tukey tests were used to determine the significance of differences between the means of different conditions.
151 Different potting media were not compared directly to each other, because their compacted volumes and initial
152 moisture levels were not standardised for this study.

153 Two simple models were created to estimate the WHC of the medium itself in containers with drainage layers.
154 In both models, the initial mass of the medium in each trial was calculated using the initial mass of the full
155 container and the initial mass of the corresponding drainage layer, $m_{i(med)} = m_{i(full)} - m_{i(drn)}$.

156 Model A was intended to estimate the highest possible WHC for the medium itself. The model was based
157 on the assumption that the drainage layer held the same amount of water after draining when in a container
158 filled with medium as when in a container alone. Thus, the drained mass of the medium in each trial was
159 calculated by subtracting the drained mass of the drainage layer from that of the full container, $m_{d(med)} =$
160 $m_{d(full)} - m_{d(drn)}$.

161 Model B was intended to estimate the lowest possible WHC for the medium itself. The model was based on the
162 assumption that the drainage layer remained fully saturated with water after draining when in a container filled
163 with medium. Thus, the drained mass of the medium in each trial was calculated by subtracting the saturated
164 mass of the drainage layer from the drained mass of the full container, $m_{d(med)} = m_{d(full)} - m_{s(drn)}$.

165 The combination of these two models provided a range of possible values for WHC of the medium alone in
166 each condition, to use as a basis for comparison against the control condition using the same depth of medium.

167 This enabled the volume and depth of the drainage layer itself to be eliminated as a factor, and the effect of the
 168 drainage layer on the medium above it to be considered in isolation.

169 3 Results

170 3.1 Coir-perlite-bark medium

171 The CPB mix showed the least compaction, with the effective volume of mix in a full pot decreasing from
 172 1,290ml to 1,133ml. The control container filled to 30mm from the top compacted from 1,030ml to 838ml, and
 173 the container filled to 60mm from the top compacted from 780ml to 672ml. The WHC of the controls increased
 174 as the depth of medium decreased.

175 The results of the CPB drainage layer trials are presented in Fig. 1. Compared to the control, every container
 176 with a drainage layer had a lower overall WHC ($p < 0.001$). There were significant differences between many of
 177 the drainage layer conditions, with the 30mm grit condition having the highest WHC and 60mm leca the lowest.
 178 Analysing only according to the drainage substrate, all had lower overall WHC than the control ($p < 0.001$).
 179 Leca had significantly lower WHC than gravel ($p < 0.05$) and grit ($p < 0.001$). Combining all substrates,
 180 both 30mm and 60mm drainage layer conditions had lower overall WHC than the control ($p < 0.001$) with no
 181 significant difference between them.

Figure 1: Mean and standard deviation water-holding capacity (WHC) of the entire container of CPB medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (***) $p < 0.001$).

182 The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 2 (30mm drainage
 183 layers) and Fig. 3 (60mm drainage layers), compared with the control containers with the same initial medium

184 depth. With both drainage layer depths, both the modeled WHC values were lower than the control values for
185 every condition.

Figure 2: Estimated mean water-holding capacity (WHC) of the CPB medium alone with different 30mm drainage layers, according to models A and B.

Figure 3: Estimated mean water-holding capacity (WHC) of the CPB medium alone with different 60mm drainage layers, according to models A and B.

3.2 Coir-vermiculite medium

The CV mix showed intermediate compaction, with the effective volume of mix in a full pot decreasing from 1,290ml to 1062ml. The control container filled to 30mm from the top compacted from 1,030ml to 816ml, and the container filled to 60mm from the top compacted from 780ml to 615ml. The WHC of the controls increased as the depth of medium decreased.

The results of the CV trials are presented in Fig. 4. Compared to the control, the gravel-30mm, grit-30mm, and leca-30mm drainage layer conditions did not have significantly different overall WHC. The grit-60mm ($p < 0.01$), gravel-60mm, leca-60mm, sand-60mm, and sand-30mm conditions ($p < 0.001$) all had lower WHC than the control. There were significant differences between many of the drainage layer conditions, with the 30mm grit condition having the highest WHC and 60mm gravel the lowest. Analysing only according to the drainage substrate, conditions with grit did not have significantly different overall WHC, while leca ($p < 0.05$), gravel ($p < 0.01$), and sand ($p < 0.001$) all had lower WHC than the control. Sand had the lowest WHC, and was significantly different ($p < 0.001$) from grit which had the highest WHC. Combining all substrates, 60mm layers had lower overall WHC ($p < 0.001$). 30mm layers were not significantly different from the control, but were significantly higher than 60mm layers ($p < 0.001$).

Figure 4: Mean and standard deviation water-holding capacity (WHC) of the entire container of CV medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (** $p < 0.01$, *** $p < 0.001$).

The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 5 (30mm drainage layers) and Fig. 6 (60mm drainage layers), compared with the control containers with the same initial medium depth. With both drainage layer depths, all the modeled WHC values were lower than the control values, with the 60mm drainage layers showing the greatest difference.

Figure 5: Estimated mean water-holding capacity (WHC) of the CV medium alone with different 30mm drainage layers, according to models A and B.

Figure 6: Estimated mean water-holding capacity (WHC) of the CV medium alone with different 60mm drainage layers, according to models A and B.

3.3 John Innes medium

The JI mix showed the most compaction, with the effective volume of mix in a full pot decreasing from 1,290ml to 925ml. The control container filled to 30mm from the top compacted from 1,030ml to 800ml, and the container filled to 60mm from the top compacted from 780ml to 590ml. The WHC of the controls was lowest for the full pot and highest for the pot filled to 60mm from the top.

The results of the JI trials are presented in Fig. 7. Compared to the control, the leca-30mm drainage layer condition had higher overall WHC ($p < 0.05$), the sand-60mm drainage layer condition had lower overall WHC ($p < 0.01$), and all other conditions were not significantly different. Analysing only according to drainage substrate, sand had lower overall WHC ($p < 0.05$), and other substrates were not significantly different. Sand had the lowest overall WHC, and was significantly different from all other substrates, while leca had the highest WHC. Combining all substrates, neither 30mm or 60mm drainage layers had significantly different overall WHC from the control.

Figure 7: Mean and standard deviation water-holding capacity (WHC) of the entire container of JI medium with different drainage layers. Asterisks mark conditions which were significantly different from the control (* $p < 0.05$, ** $p < 0.01$).

The modeled WHC of the medium itself in the drainage layer conditions is presented in Fig. 8 (30mm drainage layers) and Fig. 9 (60mm drainage layers), compared with the control containers with the same initial medium depth. For 30mm drainage layers, grit and sand had lower WHC than the control according to both models, while gravel and leca had modeled WHC values both above and below the control. For 60mm drainage layers, sand had lower WHC than the control according to both models, while all other substrates had modeled WHC values both above and below the control.

Figure 8: Estimated mean water-holding capacity (WHC) of the JI medium alone with different 30mm drainage layers, according to models A and B.

Figure 9: Estimated mean water-holding capacity (WHC) of the JI medium alone with different 60mm drainage layers, according to models A and B.

4 Discussion

The results show that adding a layer of coarse substrate below potting media will usually improve drainage of the container overall, sometimes have no effect, and is very unlikely to reduce drainage. This supports the recommendation of adding drainage layers among home gardeners, and contradicts previous theoretical predictions that such layers have a negative effect (Chalker-Scott and Downer, 2019; Evans, 2014).

The addition of drainage layers made a greater improvement to drainage when the potting media was coarser and more porous. This may be due to the similarity in pore size improving the capillary movement of water through the interface between different materials (Smesrud and Selker, 2001). This explanation is also supported by the fact that the loam-based John Innes media had the most improvement in drainage when using a substrate of 1-2mm sand, the smallest particle size which can therefore be assumed to have a pore size closest to the JI medium itself.

Thicker layers of drainage substrate tended to improve drainage more than thinner layers. This could be due to the perched water table of the drainage substrate itself making up a smaller proportion of the volume of the deeper layer. There was no apparent difference in drainage effects between porous and non-porous drainage substrates of the same particle size (leca and gravel). This may be because leca is slow to absorb water, and holds onto water at high tensions (Spomer, 1998). Thus, the leca in the drainage layer would not absorb significant quantities of water in the short time the container is saturated before drainage, and would therefore behave similarly to non-porous gravel of the same particle size.

For a very coarse loamless medium such as the CPB mix, the results show that any drainage substrate of any depth can be used to good effect to improve drainage. For a finer loamless medium such as the CV mix, a 60mm drainage layer is recommended, but any substrate is effective. For a loam-based medium such as John Innes, a 60mm layer of coarse sand is recommended for the best improvement to drainage.

245 The two different models for WHC of the potting medium alone were intended to provide the widest possible
246 range of values, as a starting point for analysis. From visual examination (Fig. A.1), the drainage layers in
247 containers with loamless potting media seemed to have approximately the same perched water table depth as
248 when alone. Thus, for the CV and CPB media, the predictions of model A are likely to be most accurate for the
249 WHC of the medium alone. For these media both models showed that all drainage layers reduce WHC, so the
250 choice of model for analysis does not significantly change the conclusions.

251 In contrast, the drainage layers in containers with JI medium seemed to remain almost completely saturated
252 after drainage (Fig. A.2). Thus, for JI medium the predictions of model B are likely to be most accurate for the
253 WHC of the medium alone. The predictions of model B showed that all substrates decreased WHC, whereas
254 model A showed a decrease for some substrates and an increase for others. Thus if model B is considered to
255 be more accurate, it can be concluded that all drainage layers reduce WHC in the medium itself, whereas only
256 some drainage layers reduced WHC in the container as a whole. More detailed study is required to confirm
257 these predictions and validate the models.

258 When considering the effect of drainage layers on growing plants, it must be remembered that such a container
259 has much more complex contents than a container of pure potting medium. There are two different materials in
260 layers, and each layer has an air-filled volume at the top and a water-saturated volume at the bottom, giving a
261 stratified effect in the pot. Further study is required to determine whether the roots of a growing plant remain in
262 the main volume of potting medium or grow down into the drainage substrate. If roots do not enter the drainage
263 substrate, then the more relevant conclusions are from the modelled results for WHC of the potting medium
264 alone, and the container should be considered to have a reduced effective volume compared to the same
265 container filled with pure medium. Whereas if roots do enter the drainage substrate, then the more relevant
266 conclusions are from the WHC of the container as a whole, and further study is also required to determine how
267 plants are affected by the alternating layers of air and water throughout the container.

268 **5 Conclusions**

269 Adding drainage layers had almost universally either beneficial or neutral effects on drainage of potting media.
270 Coarser organic media showed the greatest improvement in drainage and fine loam-based media the least.
271 Thicker drainage layers had the most effect for all potting media, but the most effective drainage substrate to
272 use was dependent on the specific medium.

273 Warnings about the raised perched water table and increased water retention should be considered inaccurate,
274 as the present study shows that such warnings may not consider the full complexities of water behaviour
275 involved. Instead, drainage layers can be considered a potentially useful tool for growers and home gardeners
276 to reduce the water retention of a given potting medium. A 60mm layer of coarse sand was the most
277 universally-effective drainage layer with all potting media tested and therefore the best single recommendation
278 for growers.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Appendix

Figure A.1: Comparison of CPB medium with 60mm layer of grit (left) to CPB medium alone to a depth of 60mm below the top (right). In the left image, the perched water table in the medium is completely eliminated, and the low perched water table in the grit is visible.

Figure A.2: Comparison of Jl medium with 60mm layer of grit (left) to Jl medium alone to a depth of 60mm below the top (right). In the left image, the grit layer appears to be completely saturated after drainage.