Wicking bed design

The effects of different reservoir media on plant growth, water use and soil moisture in wicking beds using capillary watering

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ABSTRACT

Wicking beds are planting containers that have a reservoir of water in the lower portion providing moisture to plants using capillary action. The scientific literature has findings from a few studies that wicking beds have a higher yield and greater water use efficiency than top watered containers but no research has been found about the effects of different materials in the reservoir layer. This study investigated the capillary rise, water holding capabilities and performance in wicking bed reservoirs of several materials.

Capillary rise of water in various materials was measured in Perspex tubes. Crusher dust had the greatest capillary rise, followed by sand, fine perlite and a cocopeat/compost/sand mix. Gravel and scoria had poor capillary rise.

Wicking beds were constructed with four reservoir treatments – cocopeat mix, sand, gravel and WaterUps® with medium grade perlite as the wicking medium. A cocopeat/compost/sand mix was used as the growing medium for each reservoir treatment. A commercial potting mix was also used with a sand reservoir. Three replicates of each treatment were performed. Two crops were grown sequentially: spinach then butterhead lettuce.

For the spinach crop, the cocopeat and sand/cocopeat beds grew the greatest plant weight followed by WaterUps®, gravel, and sand/potting mix. Soil moisture at 150mm depth was lowest in gravel, followed by WaterUps®, sand/cocopeat, cocopeat and sand/potting mix.

For growing lettuce, the wicking material in the WaterUps® was changed to sand. There was no significant difference in the weight of lettuce grown in any of the treatments. Soil moisture at 150mm depth remained reasonably constant throughout the growing period for WaterUps® and cocopeat. Gravel and sand/potting mix dried the most. The potting mix remained wettest of all treatments at 200mm depth but was driest at 100 and 50mm depths indicating that it had poor capillary rise capabilities.

This study found the reservoir material has an effect on the soil moisture and plant growth in wicking beds. Although often used, gravel appears a poor choice since it results in the driest growing medium. The reservoirs with cocopeat mix and sand delivered better soil moisture and plant growth. WaterUps® with sand as the wicking material also delivered a high level of soil moisture.

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1 INTRODUCTION

Wicking beds are planting containers that have a reservoir of water in the lower portion and a growing medium above. Water from the reservoir wicks up through the growing medium to supply the plants. Figure 1 shows a typical wicking bed design. Various wicking media such as gravel, scoria, sand, woodchips, soil and plastic frameworks have been proposed for filling the reservoir layer. In some designs a layer of geotextile is used above the reservoir layer to prevent the growing medium from mixing with the reservoir. Other common features of wicking beds include an overflow outlet at the top of the reservoir layer to prevent excess water from flooding the growing medium, and a fill pipe that allows delivery of water directly into the reservoir layer.

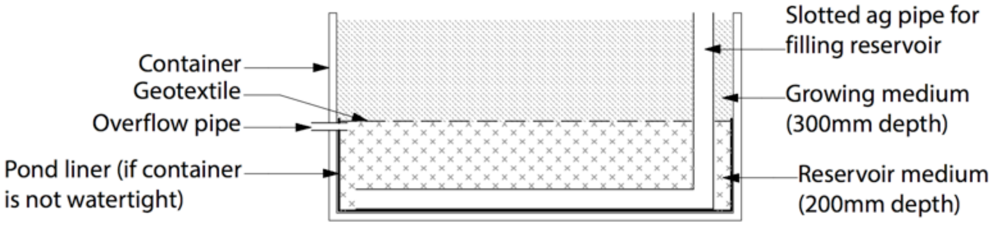

Figure 1 - Cross section of typical wicking bed design showing the major components

The beds are a popular way of growing vegetables in home gardens and have been used in some small scale urban farms. Apart from in these urban farms, wicking beds do not appear to be used to any significant extent in commercial horticulture.

Little has been written in the scientific literature about wicking beds but there are many articles about them in the popular press. These range from publishers that may be thought to have some authority, such as ABC's *Gardening Australia*, to people with unknown experience publishing blogs or YouTube videos.

Only three scientific papers describing research into wicking beds have been found. All these papers concentrated on comparing yield and water use efficiency of wicking beds with conventional planters and did not investigate alternate wicking bed designs or media to any great extent. However, papers dealing with subirrigation of plants in containers in the nursery industry and aspects of hydroponic production may provide useful guidance for the design of wicking beds. A review of literature about capillary irrigation noted the almost complete lack of published papers on wicking beds and commented that:

> *“Due to the lack of research on wicking beds, we contend that there is a specific - and very important - knowledge gap relating to the verification of performance, and of design guidance, of wicking beds.” (Semananda, Ward, & Myers, 2018)*

One of the major differences in wicking bed designs that appear in the internet and in popular publications is the question of what to use in the reservoir layer of a wicking bed. To be effective, the reservoir medium must meet a number of criteria including:

- sufficient structural strength to support the growing medium above the reservoir
- the ability to wick water from the full depth of the reservoir to the growing medium
- the ability to wick water at a sufficient rate to match evapotranspiration of the plants growing in the wicking bed
- sufficient pore space to store an adequate volume of water within the reservoir; the larger the pore space the more water can be held and the longer the interval between watering events
- not having any detrimental effect on the growth of plants in the wicking bed.

Because of the popularity of wicking beds among sections of the gardening community and the diversity of unverified designs that are being proposed in the popular literature and social media, there is a need for rigorous research to compare various wicking bed designs. This research was undertaken to, at least partially, fill that knowledge gap.

Research aims

The main aim of this project was to examine and compare plant growth and water movement by capillary action in wicking beds using different media in the water reservoir layer in order to determine the best reservoir media for use in wicking beds. The hypothesis that was tested by this research was that the choice of material used in the reservoir layer of a wicking bed affects plant growth and moisture distribution within the growing media.

To achieve this aim, the research objectives were:

1) to determine the rate and extent of upward water movement by capillary action in the various potential reservoir media.

2) to compare saturated water holding capacity of common reservoir media and assess the impact of this on how often the reservoir needs to be refilled.
3) to identify the effects of different wicking media on soil moisture and water use within wicking beds.
4) to assess the impact of wicking bed design on plant growth.

2 REVIEW OF LITERATURE

This chapter presents a summary of the published literature on wicking beds. Because of the limited amount of wicking bed research that has been published, literature on other topics that are relevant to the design and operation of wicking beds is also reviewed. These topics include: subirrigation of container plants, capillary rise in soils, saturated capacity of soils, growing media for container planting, the effects of soil moisture content on plant growth, and accumulation of salts on the surface of planting containers.

A summary of selected wicking bed articles in the popular press is attached at appendix 1.

2.1 Wicking beds

Three papers present research into wicking beds. Semananda, Ward, and Myers (2016) compared the yield and water use efficiency of tomatoes grown in wicking beds and surface irrigated containers, Sullivan, Hallaran, Sogorka, and Weinkle (2015) compared the yield of tomatoes grown in wicking beds with top watered raised planters and the number of irrigation events for each, and Semananda, Ward, and Myers (2020) compared yield and water use efficiency of lettuce and radish in wicking beds and surface watered pots both with and without a mulch layer. Beyond this, there appears to be no published research specifically involving wicking beds. In a review of subirrigation literature, Semananda et al. (2018) recommend that further research should be done into soil properties and depths of the reservoir and growing media for wicking beds.

Semananda et al. (2016) used wicking beds with gravel in the reservoir covered with geotextile and a “poorly graded sandy soil” as the growing medium. Reservoir depths were 150mm and 300mm and soil depths were 300mm and 600mm. One wicking bed treatment had a wick of soil extending into the reservoir layer. The yield of marketable tomatoes was higher in all wicking bed treatments than the surface irrigated containers, but the deeper soil produced no more marketable fruit than the shallower soil. Water use efficiency (WUE) was greater in the wicking beds with 300mm deep soil than the 300mm deep surface watered containers, but there was no difference in WUE between the 600mm deep wicking beds and surface watered containers.

The depth of the reservoir layer (150mm or 300mm) used by Semananda et al. (2016) did not affect the WUE of the wicking beds. Water was added to the wicking beds when the average soil moisture dropped below 75% of field capacity and the reservoir depth did not affect the number of watering events required. Although the wicking bed design included a clear tube as a manometer to view the water level in the reservoir, no information was provided about the water levels in the reservoir when the soil had dried to a point where irrigation was required. This may suggest that the gravel in the reservoir layer could not wick water higher than 150mm and that the water in the bottom half of the 300mm deep reservoir was not used. It is reasonable to assume that the finer textured soil would have greater capacity for capillary rise than the gravel and that using a column of soil as a wick into the reservoir layer would allow more of the reservoir water to be used and thus require less frequent water applications. However, the wicking bed with a 300mm deep reservoir and a soil wick needed the same number of irrigation events as the wicking beds with just gravel in the reservoir. Semananda et al. (2016) did not measure the wicking capability of the soil so it is unknown how effective the soil wick would have been at moving water into the upper layers of the soil compared with gravel.

The productivity of wicking beds compared with conventional raised beds was also investigated by Sullivan et al. (2015) who described them as "subirrigated planters" rather than wicking beds but they met the definition of wicking beds by having an integrated reservoir layer in the base of the beds. These wicking beds had a void in the reservoir layer created by a coil of flexible drainage tubing to create a 100mm deep reservoir. Wicking beds were tested both with and without a layer of landscape fabric separating the reservoir and growing medium. The growing medium was a 460mm deep layer of commercial potting mix comprised of a mix of compost, peat and perlite. It was not explicitly stated by the authors, but it can be inferred from their design diagrams, that some of the potting mix would have filled spaces around the outside of the drainage pipe and thus provided a capillary path from the base of the reservoir into the growing medium.

There was no significant difference in the production of cherry tomatoes between the wicking beds with and without the landscape fabric barrier, and the wicking bed without landscape fabric produced a slightly larger crop of tomatoes than the conventional raised bed planter (Sullivan et al., 2015). This study found that the wicking beds required one fifth of the watering events of the conventional beds but did not record the quantity of water applied to the wicking or conventional beds.

Wicking beds with a 150mm deep gravel reservoir and 300mm of soil had greater water use efficiency and plant yield than conventionally watered containers growing lettuce and radish (Semananda et al., 2020). The wicking beds were refilled every two weeks with an amount of water based on the drop in soil moisture, but the variation in water levels within the reservoir is not reported. Yield was also higher in beds with a layer of gravel mulch on the surface.

The research to date on wicking beds has been very limited and leaves many areas unexplored. For example, there has been no comparison of different reservoir materials or growing media, little reporting of moisture levels in the growing media, and no measurement of how much of the water contained in the reservoir is used in the wicking bed before more water needs to be added.

2.2 Sub-irrigation

Subirrigation systems provide water and often fertiliser solutions to the base of containers. Water and nutrients are then transported to the roots of the plant in the containers by capillary action through the growing medium (Ferrarezi, Weaver, Van Iersel, & Testezlaf, 2015). Various forms of capillary or subirrigation are used in the commercial hydroponics industry and there has been much more research published about these systems than about wicking beds. Although these subirrigation systems do not have the integrated water reservoir of wicking beds, they are similar to wicking beds in that they rely on capillary rise to move water into and through the growing medium and thus much of the research into subirrigation systems is potentially applicable to wicking bed systems.

Subsurface irrigation includes capillary mats, troughs, and flooded trays, benches and floors (also called ebb-and-flow systems) (Raviv & Lieth, 2008). In flooded benches and other ebb and flow systems, plant containers are placed on raised waterproof benches with low sides. Periodically, the benches are filled with water pumped from a reservoir and the base of the containers are flooded. After sufficient water has risen into the pots through capillary action, the benches are drained with the excess water returned to the reservoir. Flooded floor systems are similar but on a larger scale where the whole floor of the growing area is periodically flooded (Ferrarezi, Weaver, et al., 2015). The flooding level does not have to be deep and the growing medium can be fully wet by a depth of about one fifth of the container height (Evans, Barrett, Harbaugh, & Clark, 1992). In trough systems, containers are placed in gently sloped troughs and water pumped into the higher end of the trough. Any water not absorbed by the plants is drained from the lower end of the trough into the reservoir (Semananda et al., 2018). Capillary mat systems consist of an absorbent fabric with an underneath layer of waterproof plastic and a covering of perforated plastic. The mat is placed on horizontal benches and flooded with water. Plant pots with holes in their base are placed on the perforated surface of the mat and water wicks into the growing medium by capillary action. The perforated covering allows water through into the pots while preventing evaporation from unused areas of the mat. Providing the media used is fine enough to allow capillary rise, pots up to 21cm high are suitable for use with capillary mats (Schuch & Kelly, 2006).

Subirrigation systems have been developed to capture and recycle unused nutrient solutions. This has become necessary due to increasing environmental and legal requirements to minimise leaching and drainage of excess nutrients away from plant production sites (Roeber, 2010; Yeager & Henley, 2004). Systems have been developed to capture and recycle drainage from top-watered containers but the risk of spreading pathogens between containers in this type of system is high. There is less risk in recycling nutrient solutions from subirrigated containers because most of the unused nutrient solution has not been in contact with the media in the containers (Biernbaum, 1992; Roeber, 2010). George, Biernbaum, and Stephens (1990) grew geranium seedlings in an ebb and flow system with a shared nutrient solution reservoir. Some pots were inoculated with varying levels of *Pithium ultimum* and other pots were not inoculated. After eight weeks, all plants in inoculated pots showed effects of the disease but none of the uninoculated plants were affected. However, the reservoirs of the trays containing pots with the highest level of inoculation did contain *P. ultimum* and this may have spread to the unaffected plants if the experiment was continued for longer. Wicking beds address the issue of disease spread firstly by not having any excess water that needs to be prevented from leaving the site, and secondly by having a separate reservoir for each container and thus having no risk of spreading pathogens through sharing of solutions.

As well as reducing the amount of water used compared with top watering, subirrigation can result in greater shoot growth and higher shoot/root ratio than overhead watering (Frangi, Amoroso, Piatti, & Faoro, 2011; Piatti, Frangi, & Amoroso, 2011). Greater shoot and root growth was observed in wheat plants watered from below compared with top-watered plants (Singh, 1922). The continuous supply of water and nutrients from the capillary mat limits water stress and reduces the need for root growth, thus allowing greater shoot growth. Frangi et al. (2011) also found that leaves of the plants grown on the capillary mat had a higher nitrogen, phosphorus and potassium levels than the overhead watered plants.

One key difference between wicking beds and most subirrigation used in commercial hydroponic systems is that the water reservoir is constantly supplying water to the growing medium in a wicking bed whereas subirrigation systems typically use intermittent watering that allows some drying of the growing media between irrigation events. What effect this difference may have on growing media selection or plant growth in wicking beds does not appear to have been examined.

2.3 Capillary rise

Capillary rise of water through the reservoir and growing media is the method by which water travels from the reservoir to the plant roots in a wicking bed. Therefore, the capillary rise capability of the media used should affect the operation and productivity of a wicking bed. Important characteristics of capillary rise are the height of capillary rise within the medium, the water storage capacity of the capillary system, and the amount of water that can be transported to the root zone via capillary rise in a given time (Liu, Yasufuku, Miao, & Ren, 2014). A review by Salim (2016) indicates that there were contradictory values for the height of capillary rise in sands, silts and clays, and that most quoted figures are estimates based on mathematical models, rather than measured values.

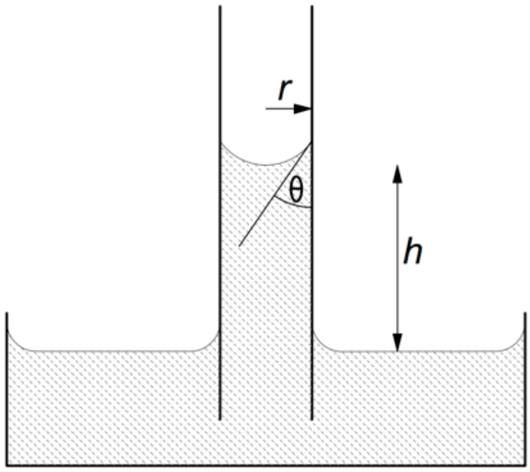

Figure 2 - Capillary rise (h) of liquid in a tube or radius (r) showing contact angle (Θ)

Factors that affect capillary rise include the diameter of the tube formed by the grains of the medium, the contact angle between the liquid and the solid surface, the density and viscosity of the liquid, and the amount of surface tension. Capillary rise is inversely related to the size of the tube; large pores formed between large particles will have less capillary rise than small pores formed by small particles. The hydrophobic/hydrophilic properties of the surface will affect the contact angle. If the surface is hydrophilic the contact angle will approach 180° and the surface will wet and capillary rise will occur. If the surface is hydrophobic, the contact angle will approach 0°, the surface will remain dry and no capillary rise will occur. However, soils are not uniform; tube diameters are not consistent, tubes are not continuous, and the nature of the particle surfaces vary. This creates difficulties in applying mathematical models of capillary rise to real soils (Salim, 2016).

Keen (1919) gives a formula (1) for estimating capillary rise in an ideal homogenous soil with spherical grains.

$$h = \frac{4\sqrt{3T}}{\rho g K} \qquad (1)$$

where h is the height of capillary rise, T is surface tension, ρ is density of water, g is the force of gravity and K is the side of an equilateral triangle approximating the pore size. After applying some assumptions about values for surface tension, gravity and density, equation 1 is simplified to:

$$h = \frac{0.75}{r} \qquad (2)$$

where r is the radius of the soil particles and the units are centimetres.

Keen notes that values are likely to be less in field conditions due to non-uniformity of soil particles. Washburn (1921) developed equation (3) to define the distance a liquid will flow through a capillary tube was developed by Washburn (1921) which has been widely used as the basis for further work.

$$d = \sqrt{\frac{\gamma rt.cos\theta}{2\eta}} \tag{3}$$

where d = distance of flow, γ = surface tension, r = pore radius, θ = contact angle and η = viscosity.

The Young-Laplace equation (4) is widely used to calculate vertical capillary rise (h_c). It is based on work by Thomas Young in 1805 and Pierre-Simon Laplace in 1806 (Masoodi & Pillai, 2012).

$$h_c = \frac{2\gamma.cos\theta}{\rho gr} \tag{4}$$

Lu and Likos (2004) compare the Washburn equation and his experimental results with calculations based on Terzaghi's 1943 book (*Theoretical Soil Mechanics*) and develop their own equations to predict capillary movement of water in soils.

Capillary rise in sand and loam is affected by moisture content and hydrophobicity of the surfaces. Examination of movie films of the wetting front in soils sandwiched between two glass plates showed that capillary rise is not continuous at a constant rate, but rather proceeds in a series of irregular movements (Wladitchensky, 1966). The process leading to this irregular movement, as described by Wladitchensky (1966), is:

> *"According to all these considerations one may picture the mechanism of capillary movement of water in a single pore as following. The water penetrates into a pore, wets with a thin film the pore walls, the wetted pore wall surface being greater when the wetting of walls is more perfect. The film 'tows' the water column. As the weight of water column increases the curvature of the water surface on the upper boundary of the water column decreases. This process proceeds until the surface reaches the curvature of static wetting angle. At this moment the capillary movement ceases. If the pore wall above the static meniscus edge can adsorb moisture, the capillary rise does not end. The pore surface adsorbs water vapour, water condensation occurs, and a film of adsorbed water is formed on the pore-wall. The wetting of the solid phase increases. A water film is formed again. This film gives rise to a new jump of capillary water to the boundary of the next more hydrophobic part of pore wall surface."*

(Keen, 1919) reports results from Loughbridge on capillary rise in four Californian soils that showed a faster rate of rise in coarser textured (sandy) soil, slower rise in fine textured (clay) soil, and a higher total rise in fine textured soil (50 inches) than in sandy soil (16.5 inches). The level of water in the finer soils was still rising after 195 days.

Results from field trials with in-situ soil showed that capillary rise was slow and not to a great height but also showed a greater capillary rise in sandy loam than clay loam (Bouyoucos, 1947). A further report on these field trials (Bouyoucos, 1953) concludes that capillary rise is too small and too slow to provide water to plants in field conditions. The author suggests that rather than plants obtaining water from capillary rise, roots grow fast to find available water. Bouyoucos (1953) suggests reasons why capillary rise doesn't happen in practice: 1) soil holds on to water more as moisture tension rises preventing free movement of water; and 2) water movement is impeded by friction in capillaries, translocation and swelling of colloids blocking capillaries, air pockets blocking capillaries, and water films and capillaries becoming discontinuous.

Laboratory experiments have demonstrated that the height of capillary rise is affected by the cross-sectional area of the container. Wadsworth and Smith (1926) conducted an experiment with square glass-fronted columns filled with screened soil placed in a container of water. Total capillary rise increased with an increase in the cross-section of the soil column from one square inch up to 25 square inches. The height of maximum water content above the free water table also increased with cross-sectional area up to 16 square inches. The rate of capillary rise was faster in the larger columns and the smaller columns reached the maximum height in less time than the larger columns. The authors were not able to explain why these results occurred.

Research conducted by Albaho (2006) demonstrated that the cross-sectional area of wicks supplying water to potted plants affected the amount of water uptake. Tomatoes growing in pots suspended over a water reservoir with wicks extending from the base of the pots down to the water produced more high quality fruit when the cross-sectional area of the wicks and the growing medium was larger. During high water demand at flowering and fruit expansion growth stages, more water was taken up by wicks with a larger cross-sectional area. These findings may be significant when evaluating the performance of wicking beds that use a limited wicking area (for example: WaterUps® - www.WaterUps.com.au) compared to sand or gravel wicking beds where the entire cross-sectional area of the bed can wick water.

Raes and Deproost (2003) note that calculating the rate of upward movement of water in soil depends on, as well as the capillary properties of the soil, the depth to the water table, the water content in the root zone, water up-take characteristics of the plant roots, and the evapotranspiration rate. They have developed a computer program UPFLOW (Raes, 2004) available from iupware.be/?page_id=883 that uses input parameters for these and other factors and predicts the order of magnitude of the likely capillary rise. Utilities such as these may be useful in determining the efficacy of different wicking bed designs.

Organic compounds derived from decomposing or living microorganisms or plants can cause soil to become water repellent or hydrophobic and resist wetting for a period. This can reduce the amount of capillary rise or result in preferential water pathways and uneven wetting through the growing medium (Raviv & Lieth, 2008). No capillary rise occurred in air dried hydrophobic peats but hydrophobicity dropped as water potential (wetness of media) increased (Michel, Rivière, & Bellon‐Fontaine, 2001). Pike (1979) recommended that to establish a water column through the medium and start capillary watering it was necessary to first water the pots from overhead. This may serve to evenly wet the medium in the pots and avoid these problems described above. However, most researchers experimenting with subirrigation do not mention this. Exceptions are Hoffman, Buxton, and Weston (1996) and Wilfret and Harbaugh (1977) who moistened the soil in pots before placing the pots on capillary matting.

Capillary rise is related to the unsaturated hydraulic conductivity of the soil. Substrates that have poor unsaturated hydraulic conductivity will not distribute water adequately above the level to which the base of the root zone is flooded (Raviv & Lieth, 2008). Unsaturated hydraulic conductivity depends on many factors such as the pore-size distribution of the medium, and the tortuosity, shape, roughness, and degree of interconnectedness of the pores. The hydraulic conductivity decreases considerably as soil becomes unsaturated since less pore space is filled with water, the flow paths become increasingly tortuous, and drag forces between the fluid and the solid phases increase (Lu & Likos, 2004; van Genuchten & Pachepsky, 2011). Unsaturated hydraulic conductivity at a given potential can be raised by increasing the proportion of fines in a porous medium. Adding fine material to coarse substrates can therefore be expected to increase capillary rise (Caron, Elrick, Beeson, & Boudreau, 2005; Heiskanen, 1999).

The scientific literature on capillary rise debunks a "fact" that frequently appears in the popular articles about wicking beds: that water will not wick up more than 250 or 300mm. Providing a suitable medium is used, that is clearly not true. The evidence presented in the literature demonstrates that large particle sizes reduce wicking, and this casts doubt on the common practice of using gravel in the reservoir layer of wicking beds. However, the actual performance of such media in wicking beds has not been measured.

2.4 Saturated water holding capacity

The reservoir layer of a wicking bed has two main functions: to wick the water up to the growing media so it is available to plants (as described above) and to store water that can be used to wet the growing media. The amount of water that can be stored in the reservoir media is related to the saturated water capacity of the media.

Water is stored in the pores between the solid particles in the media. The porosity of a medium can be calculated from its bulk density and particle density and, in theory, when the medium is saturated all the pore space is occupied by water (Rose, 1966). Most horticultural, agricultural and engineering applications are more interested in how fast water drains from a medium once the water content is above field capacity rather than the total amount of water a medium can store. However, the water holding capacity is of interest when designing drainage trenches for applications like septic tanks or stormwater drainage where it can be advantageous to temporarily store water when inflows exceed the infiltration rate of the soil surrounding the trench (Quisenberry, Brown, & Smith, 2006; Sieker, 1998).

Quisenberry et al. (2006) measured the storage capacity of several subsurface waste storage products including a gravel filled trench. They found that the measured capacity of the gravel filled trench was the same as the calculated capacity based on the volume of the trench and the measured porosity of the gravel. However, they also stated, without explanation, that 10% difference between the measured and calculated capacities of gravel systems can be expected.

There is a high correlation between the saturated water capacity of a soil and both the bulk density and organic content of the soil. This was demonstrated by Yi, Li, and Yin (2013) who developed artificial intelligence systems to predict the saturated and field capacity of soil based on the amount of clay, silt and sand, the bulk density and the organic matter content of the soil.

2.5 Growing media

The growing media layer in a wicking bed needs to provide a suitable rhizosphere environment for the growing plants. It should provide physical support for the roots and the above ground parts of the plants, have adequate water holding capacity, contain air-filled pores to provide oxygen and provide a nutrient supply to the plants (Wilkinson, Landis, Haase, Daley, & Dumroese, 2014). In hydroponic growing, plants are grown in nutrient enriched water and therefore the nutrient holding capacity of the media is of little concern. For wicking beds, the growing media must hold and supply the nutrients needed by the plants.

Wicking beds are a form of container growing and the media used in them must, in some way, be artificially constructed (even if it is just removing soil from the ground and placing it in the wicking bed). Media developed for container growing where overhead irrigation is used generally have good drainage characteristics and high air-filled porosities. The larger particle sizes that provide these characteristics result in poor capillary rise properties that make them less than ideal for subirrigation (Caron et al., 2005). In 2002, Boudreau et al. (cited in (Caron et al., 2005) found that the efficiency of capillary mat systems was being limited by the substrates then in use. In very light and open mixes water does not reach the upper levels of the pots due to a reduced number of capillary pores. A tighter mix with more fine particles provides a better capillary path and the greater the height of the pot, the tighter the mix needs to be to transport water to the top (Evans et al., 1992). Peat, perlite, rockwool, bark, compost and mixes of these materials are all used in subirrigation systems (Semananda et al., 2018). Therefore, careful consideration is required when developing the growing media to be used in wicking beds.

Early work in developing artificial mixes for container growing was done at University of California. (Matkin & Chandler, 1957) described five soil mixes with varying percentages of fine sand, sphagnum peat moss and fertiliser. The combination of fine sand and peat provided a reproducible medium that had similar water and nutrient retention capabilities to loam. They recommend either 50:50 or 25:75 sand:peat moss mix for use in pots. "Peat-lite" potting mixes were developed at Cornell University in the 1960's and this work provides the background for many modern potting mixes (Boodley & Sheldrake, 1972). The peat-lite mixes vary based upon intended use, with 50% sphagnum peat combined with either 50% vermiculite (mix A), 50% perlite (mix B) or 25% vermiculite and 25% perlite (mix C). However, the capillary rise properties have not been reported for the UC or Cornell peat-lite mixes.

When considering the properties of peat and its role within the growing medium, the source plant may be a critical consideration. Sphagnum peat, derived from mosses, is composed of structures that have a network of hollow vessels and pores that provide a large capacity for holding water and good capillary rise properties. Sedge peat is decayed grasses and does not have the same hollow fibrous structure. Water retention and capillary movement in sedge peat is largely in the spaces between, instead of within, the fibres and this is less effective than in sphagnum peat (Caron et al., 2005). Because of these properties, sphagnum peat is more widely used in horticultural applications than sedge peat, although both are used.

The advantages of peat moss include its ability to hold large amounts of water, air and nutrients and it is widely used in container growing media, particularly in North America and Europe but concerns have been raised about the environmental impacts of continuing to mine ancient peat bogs (Robertson, 1993). Alternatives to peat include composts, coconut coir, fresh or composted rice hulls, and pumice. Composted bark is now widely used as the main ingredient in potting mixes (Landis & Morgan, 2009). In a trial using composted municipal solid waste (MSW) to grow woody plants (*Cotoneaster*), the plants performed poorly in 100% composted bark or MSW (40g shoot dry weight) but good growth occurred in mixes of MSW and at least 25% peat (60-70g shoot dry weight) (Hicklenton, Rodd, & Warman, 2001).

Coir is frequently used as a substitute for peat. It is a by-product of the coconut industry and therefore may be regarded to have some improved environmental credentials, although transport impacts from tropical regions where it is produced are significant (Landis & Morgan, 2009). If experimental results using peat are to be interpreted with a view to substituting coir for peat, it is important to understand the comparative performance of the two media. Compared with peat based mixes, coir has higher aeration, lower water holding capacity, less easily available water and, at water tension above 2.5kPa or volumetric water content below 40%, greater hydraulic conductivity (Abad et al., 2005; Londra, 2010; Raviv, Lieth, & Wallach, 2001). No studies have been found that investigated capillary rise properties of coir. Londra (2010) surmised that due to the higher hydraulic conductivity, the coir based mix would be better able to meet plant water demands during high periods of evapotranspiration. This may indicate that coir would be a good ingredient in a substrate mix for use in wicking beds.

Much work has been done in comparing top watering with various types of subirrigation (Colla et al., 2003; Cox, 2001; Elia, Santamaria, Parente, & Serio, 2003; Frangi et al., 2011; Klock-Moore & Broschat, 2001; Santamaria, Campanile, Parente, & Elia, 2003). Results from these studies vary and it is not possible to definitively conclude that one method of irrigation is better in all circumstances. Usually, the same medium has been used in both the top-watered and subirrigated samples and no consideration has been given to the different physical requirements that the different irrigation systems may impose on the media. Comparisons of an ideal medium for subirrigation with an ideal medium for top watering may produce different results.

Some work has been done to compare the effectiveness of different media with subirrigation. Water content of two media (peatmoss and perlite 7:3 and 5:5 (v/v)) in three sub-irrigated systems (nutrient flow wick, nutrient stagnant wick and ebb-and-flow) was higher in media with greater amount of peatmoss in all irrigation systems and was higher in smaller pots (6.3cm high) than larger pots (9 and 13.5cm high) (Oh, Cho, Kim, & Son, 2007). Comparison of three peat/composted bark/sand mixes found that a mix of 60% sphagnum peat with 30% bark and 10% sand had better capillary rise, faster plant growth, less water use and more even water potential throughout the medium than mixes with 30% sphagnum peat/60%bark/10%sand or 60% sedge peat/30% bark/10%sand (Caron et al., 2005). The best performing medium had the highest percentage of fine particles with a mean weight diameter of 2.93mm and 50% of the particles less than 1mm diameter.

Wesonga, Wainaina, Ombwara, Masinde, and Home (2014) conducted capillary rise tests on four mixes (SSM - 3 parts forest soil, 2 parts sand and 1 part manure; SCMP - 2 parts forest soil, 4 parts cocopeat, 1 part manure and 1 part pumice; SCMS - 2 parts forest soil, 4 parts cocopeat, 1 part manure and 1 part sand; CMP - 4 parts cocopeat, 1 part manure and 2 parts pumice). They found that SSM>SCMP>SCMS>CMP based on amount of water absorbed, but did not report the height of capillary rise achieved. Neither did they report the physical properties of the forest soil they used which limits the applicability of these results to other soil samples.

Perlite has shown good performance in subirrigated systems. Perlite absorbs more than twice the amount of water than pumice, peat or mixes of pumice and peat (Elia et al., 2003). However, differences between substrates can be compensated for by measuring the water tension in the substrate and adjusting the watering regime accordingly (Elia et al., 2003).

A number of questions about the best growing media for wicking beds remain. Because most subirrigated systems use pots that are not as deep as most wicking beds, the capillary rise capabilities of media to sufficient height for wicking beds has not been investigated. Most media used in subirrigated systems use significant proportions of sphagnum peat, perlite or vermiculite which have little nutrient content and reasonably high environmental impacts. The suitability and performance of media that are more sustainable and are able to supply nutrients to plants without the constant irrigation with a nutrient solution is still to be researched.

2.6 Soil moisture content

A good supply of water is essential for plant growth and soil water potential (Ψ) is a reflection of the energy that plants need to extract water from the soil. As Ψ drops below -0.25MPa, cell expansion slows; below -0.5MPa cell wall and protein synthesis slows; and photosynthesis and stomatal conductance drop at -1MPa. Around Ψ = -1.5MPa is generally regarded as permanent wilting point below which plants will not recover, although some plants are adapted to survive much lower Ψ values. Field capacity is the maximum amount of water a soil will hold after free-draining water has drained away. In natural soils this is generally Ψ between -10 and -33kPa. Too much water is also detrimental to plants. In saturated soils, pores that normally would be filled with air become filled with water, oxygen is unavailable to plant roots and root tissues become hypoxic (Taiz, Zeiger, Moller, & Murphy, 2015).

Although wicking beds can use natural soil as a growing medium, they are most frequently filled with soilless substrates (for example commercial potting mixes) or mixes of soil and soilless components. Soilless substrates differ from natural soils in that they have lower bulk densities and fewer micro-pore structures. Common practice is to irrigate soilless media to maintain much higher water potentials than is usual with soils. At a tension of -1kPa, soilless media generally has sufficient air-filled pores, and plant growth slows below optimal when tension is below -10kPa (de Boodt & Verdonck, 1972).

Oh et al. (2007) reported that, at the time, few studies had investigated an optimum water content for soilless media. However, numerous researchers have reported the water contents that were measured during subirrigation experiments. Maximum volumetric water content in 6cm diameter pots (pot height or volume not stated) filled with 7:3 mixture of peat moss and perlite subject to different subirrigation methods varied between 60% (ebb and flow irrigation) and 30% (nutrient flow wick system). These moisture levels produced good growth in *Kalanchoe blossfeldiana* with plants after 10 weeks having an average height of 24.9cm, 468.7cm^2 leaf area and 4.24g shoot dry weight (Son, Oh, Lu, Kim, & Giacomelli, 2006).

Ferrarezi, van Iersel, and Testezlaf (2015) grew rooted hibiscus cuttings in 12cm high pots, with a peat/perlite mix and ebb and flow subirrigation. Irrigation was provided for a fixed time when the volumetric water content of pots reached a set threshold between 10% and 42% volumetric water content. Shoot height and dry weight increased with increasing thresholds for triggering irrigation events. The maximum water content after irrigation was 70% at the 10% threshold, and 90% at the 42% threshold. Capillary rise was slower in the drier pots due to soilless media having a low hydraulic conductivity at low water contents.

Spinach yield and nutritional quality is affected by water availability. Spinach grown in sandy soil with a closely controlled soil water matric head of -20 to -30 cm had faster growth, higher yield and better quality than spinach grown at matric heads of -10 to -20 cm or -30 to -40 cm (Nishihara, Inoue, Kondo, Takahashi, & Nakata, 2001).

Despite the practice being to grow plants in soilless substrates at high water potentials, they can survive very low potentials. Mature marigold plants in a peat/vermiculite/perlite mix exhibited first signs of wilt at -0.6Mpa (12.8% volumetric moisture content) and severe wilt at -2.2MPa (4.8% moisture content). After re-watering, all plants appeared to completely recover (Fields, Fonteno, & Jackson, 2014).

Small changes in water tension do not affect yield of tomatoes. Capillary mat irrigation from a trough with water 7, 10 and 14cm below the growing medium maintained water tensions of -1.0, -1.6 and -2.0kPa in the medium but did not cause any difference in yield (Saarinen & Reinikainen, 1995).

There have been no papers published on the soil moisture content achieved in wicking beds and whether or not wicking beds can supply sufficient moisture for optimum growth. Semananda et al. (2016) refilled their wicking beds when moisture content dropped below 75% of field capacity but did not report what that moisture content was.

2.7 Surface salt accumulation

A potential problem with subirrigated containers is that salts rising with the irrigation water may accumulate near the surface of the growing medium. In top watered containers, excess irrigation can be periodically applied to leach salts out of the medium but there is no mechanism for this in subirrigation systems (Evans et al., 1992). This is potentially a constraint for plant production systems in wicking beds as excess salinity can stunt the growth of plants (Bernstein, 1975).

Several researchers have measured high electrical conductivity indicating high salt levels in subirrigated containers (Argo & Biernbaum, 1996; Colla et al., 2003; Elia et al., 2003; Kent & Reed, 1996) but high salt levels on the surface generally do not affect plant growth because in subirrigated containers most root growth occurs lower in the growing medium (Colla et al., 2003; Cox, 2001; Kent & Reed, 1996). High surface salt levels may restrict reuse of the medium because small seedlings planted in the surface layer may be affected (Cox, 2001; Evans et al., 1992).

It would appear that accumulation of salts on the surface of wicking beds could be a problem but it has not been measured. The UPFLOW program (Raes, 2004) can be used to estimate salt movement due to capillary rise. Where salt accumulation has been reported in subirrigated containers, the irrigation has been done with a nutrient solution. It is not known if wicking beds that are irrigated with plain water and use nutrients stored in the growing medium for plant growth will suffer from this problem.

3 METHODS

Two experiments were conducted to measure water holding capacity and capillary rise of various media, and three wicking bed trials were conducted in a 6m x 4m polytunnel located in Bywong, NSW (35^{o}10.558'S, 149^{o} 21.425'E, elevation 735m). The methods used to conduct these experiments are described in the following sections.

3.1 Water holding capacity

To measure the water holding capacity of various materials, rectangular plastic take-away food containers (111 x 172 x 52mm, nominal volume 650ml, actual volume 670ml) were filled with the media to level with the top of the container then weighed on certified commercial scales (CAS SW1C-10). Water was added to the media-filled containers until there was free water level with the top of the container. The water-filled containers were re-weighed to determine the total water holding capacity. The containers were then covered with aluminium flyscreen mesh (wire diameter 0.37mm, holes 1.5 x 1.5mm) and inverted onto a wire rack and left to drain until water ceased dripping through the rack. The drained containers were weighed to determine the amount of water remaining the give the field capacity of the media. The media used are listed in Table 1 and shown in Figure 3. Three replicates for each medium were performed.

Table 1 - Materials used in water holding capacity experiment

Medium	Description
Cocopeat mix	6:3:1 mix of cocopeat, compost and washed sand
Crusher dust	fine crushed rock graded from 5mm down to dust
Crushed gravel	10mm screened crushed aggregate rock sold as "blue metal"
River gravel	10mm rounded gravel
River sand	
Scoria	15mm screened volcanic rock
Washed sand	

Figure 3 - Materials used in water holding capacity experiment: A cocopeat mix, B crushed gravel, C crusher dust, D River gravel, E river sand, F scoria, G washed sand

3.2 Capillary rise

This experiment measured the rate of capillary rise of water through the selected media. One end of clear Perspex tubes (46.2mm inside diameter, 50.25mm outside diameter, 500mm length) was covered with aluminium flyscreen mesh (wire diameter 0.37mm, holes 1.5 x 1.5mm) and the tubes were filled with air dried samples of the selected media. The media was settled in the tubes by gentle manual vertical shaking of the tubes as they were being filled but not otherwise compacted. The top ends of the filled tubes were left uncovered.

The tubes were placed vertically in 750ml plastic take-away containers with the ends of the tubes supported 5mm above the base of the containers by metal spacers. The containers were filled to a depth of 35mm with 500mm of water. The containers were covered with a lid with a hole for the tube to pass through to reduce evaporation from the containers.

The height of capillary rise (wetting front) was identified by visually identifying a colour change in the media. In the case of perlite, it was not possible to see the wetting front using pure water so four drops of green food colouring was added to each container. Periodic measurements were taken of the height of the wetting front in each tube. Frequency of measurement varied with the rate of rise. At the start of each experiment measurements were taken approximately every 0.5 to 2 hours, and then approximately daily. The wetting front did not always rise evenly around the circumference of the tube. Where the rise was uneven, the median height between the highest and lowest point was used.

Table 2 - Materials used in capillary rise experiment

Medium	Description
Cocopeat mix	6:3:1 mix of cocopeat, compost and washed sand
Crusher dust	fine crushed rock graded from 5mm down to dust
Crushed gravel	10mm screened crushed aggregate rock sold as "blue metal"
Perlite(fine)	Fine grade perlite, mean particle diameter 4.67mm
Perlite(med)	Medium grade perlite, mean particle diameter 6.37mm
River gravel	10mm rounded gravel
River sand	
Scoria	15mm screened volcanic rock
Washed sand	
Woodchips	pine woodchips, 2-10mm

Three replicates were performed for each material except woodchips (2 replicates), scoria (5 replicates) and crushed gravel (4 replicates). Woodchips are rarely suggested as a reservoir material, showed only moderate wicking ability and were not to be used in the wicking bed experiments so an additional replicate was not deemed necessary. Scoria and gravel are frequently specified as reservoir material in popular literature and gravel was used by Semananda et al. (2016) and Semananda et al. (2020). The first three replicates of these materials showed poor wicking performance so additional replicates were done to ensure robustness of the results.

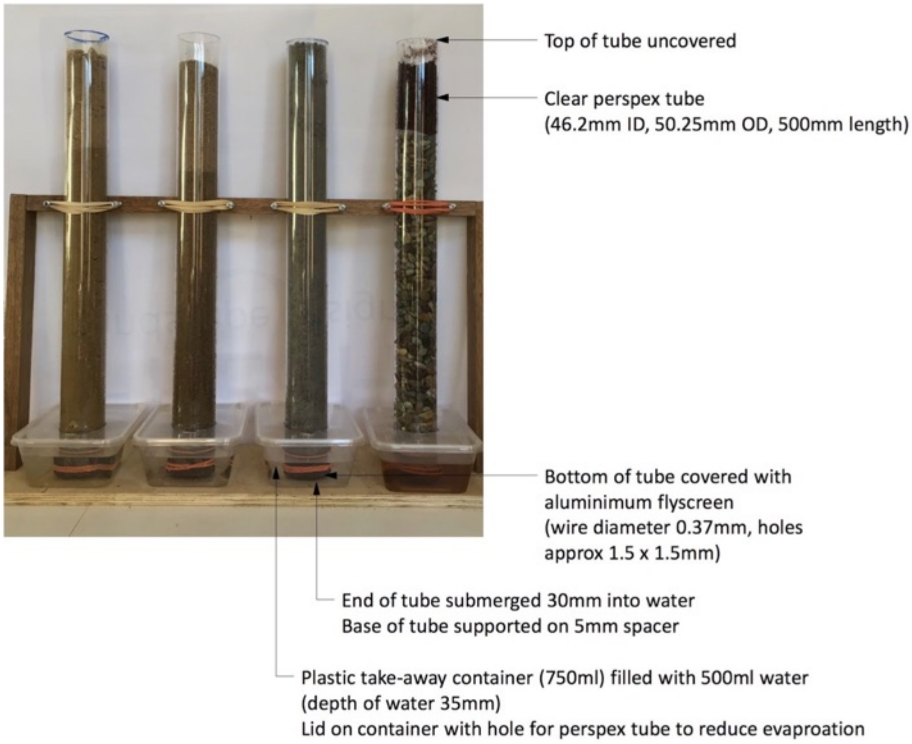

Figure 4 - Experimental apparatus used for capillary rise experiment

3.3 Wicking bed trials

Three wicking bed trials were conducted in a polytunnel in Bywong, NSW from October 2019 to April 2020. The first two experiments used the same wicking beds while the third used a different design. The three experiments are described in the following sections.

3.3.1 Wicking bed trial 1 (WBT1)

Five different combinations of reservoir and growing medium were used. Four reservoir media (cocopeat mix, 10mm crushed gravel, washed sand and WaterUps® modules) were used in conjunction with a cocopeat mix growing medium. A washed sand reservoir was also used with a commercial potting mix growing medium. Three replicates of each treatment were tested in a completely randomised design. The treatments and their allocation to beds are presented in Table 3.

The cocopeat mix was a 6:3:1 mix by volume of cocopeat fibre, municipal green waste compost and washed sand. When used in the growing layer, Scotts Osmocote Vegetable Tomato and Herb fertiliser (NPK 13.3:1.8:4.4) was added to the cocopeat mix (110g/100L of cocopeat mix). The commercial potting mix used was Scotts Osmocote Professional Premium Potting Mix. No additional fertiliser was added to the potting mix.

The WaterUps® modules are a commercial product designed to be used as the reservoir layer in wicking beds. They consist of 400 x 400mm plastic trays with four 60 x 60mm, 140mm deep hollow 'legs'. The trays support the growing medium above a water filled reservoir and the legs, filled with a wicking medium, provide a path for water from the reservoir to move to the growing medium.

Table 3 - Treatment (reservoir and growing media) and container type used for wicking beds

Bed	Treatment	Reservoir medium	Growing medium	Container[1]
1	cocopeat	cocopeat mix	cocopeat mix	B
3	sand.cp	washed sand	cocopeat mix	T
4	sand.pm	washed sand	potting mix	T
5	gravel	10mm crushed gravel	cocopeat mix	B*
6	cocopeat	cocopeat mix	cocopeat mix	B
7	sand.cp	washed sand	cocopeat mix	T
8	WaterUps®	WaterUps®	cocopeat mix	T
9	sand.pm	washed sand	potting mix	T
10	cocopeat	cocopeat mix	cocopeat mix	T
11	sand.cp	washed sand	cocopeat mix	B
12	WaterUps®	WaterUps®	cocopeat mix	B*
13	sand.pm	washed sand	potting mix	B*
14	gravel	10mm crushed gravel	cocopeat mix	B
15	WaterUps®	WaterUps®	cocopeat mix	T
16	gravel	10mm crushed gravel	cocopeat mix	T

(1)T: top half of IBC, B: bottom half of IBC, B*: bottom half of IBC with outlet

Sixteen wicking beds were constructed from Intermediate Bulk Containers (IBCs) cut in half and with a dividing panel placed vertically across each half giving beds of 950mm x 580mm and 470mm deep. Due to the shape of the IBCs, there was a small variation in volume between beds made from the top and bottom half of the IBC, and beds that incorporated the IBC outlet had approximately 5 litres less volume than other beds. Table 3 indicates which portion of the IBC was used for each bed. One of the sixteen beds was not used in the experiments.

The bottom 250mm of each bed was lined with PVC pond liner to ensure that the dividers in the middle of the IBCs were watertight. A 15mm diameter clear plastic tube was attached to an outlet in the base of each bed and extended 200mm up the side of the bed. This tube served both as an overflow outlet to ensure that the water level in the reservoir layer remained below the growing medium and as a visual indication of the level of free water in the reservoir.

Beds with cocopeat, gravel and sand reservoirs had a 50mm diameter PVC tube fill pipe to direct water to the base of the reservoir. This was connected to a 50mm diameter slotted PVC pipe that ran along the centre of the base of the reservoir to distribute water through the media (Figure 5). Where gravel or sand was used in the reservoir, a layer of geotextile fabric (Grunt Landscape Fabric, needle punched polyester fibres) was placed across the surface of the reservoir layer to separate it from the growing medium. The beds with cocopeat in both the growing and reservoir layers did not have geotextile.

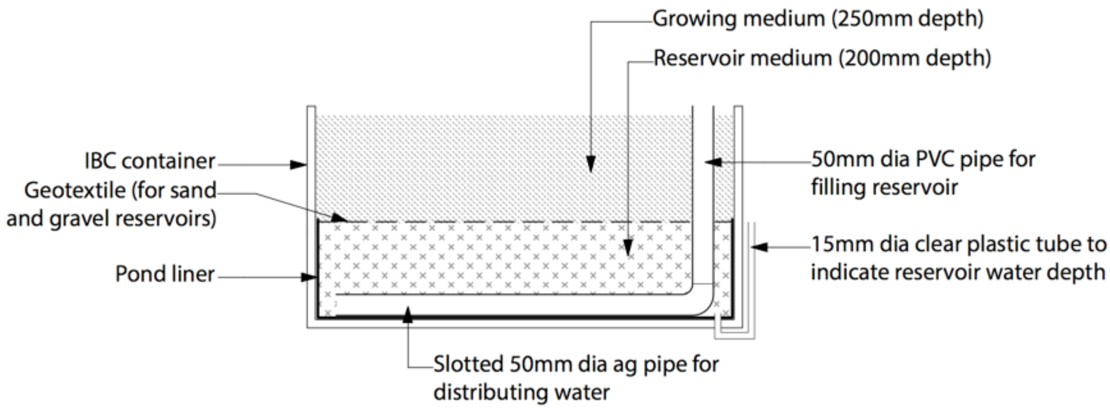

Figure 5 - Design of wicking beds with cocopeat, gravel and sand filled reservoirs

The reservoir layer was filled with the reservoir medium to a depth of 200mm. The growing layer consisted of 300mm depth of growing medium, which compacted to approximately 250mm depth after watering.

The beds with WaterUps® had a 60mm deep layer of washed sand placed in the base to raise the tops of the WaterUps® modules to 200mm above the bottom of the container. Two complete WaterUps® modules were used in each bed plus partial modules to fill the remaining area of the bed. Each bed had 12 legs filled with wicking material (Figure 6, Figure 7). In the first wicking bed experiment (WBT1), medium grade perlite was used as the growing medium in the legs of the WaterUps® modules. In the second experiment (WBT2) the perlite was replaced with washed sand.

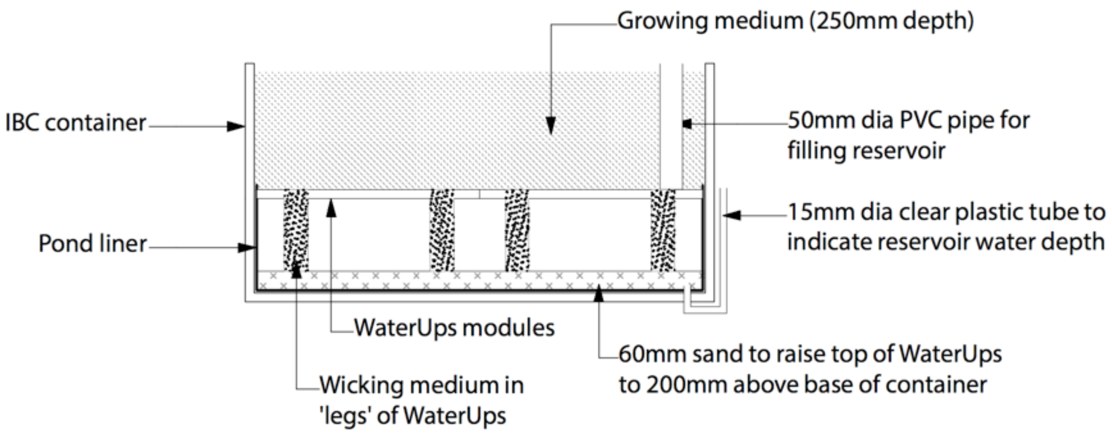

Figure 6 - Design of wicking beds using WaterUps modules in the reservoir layer

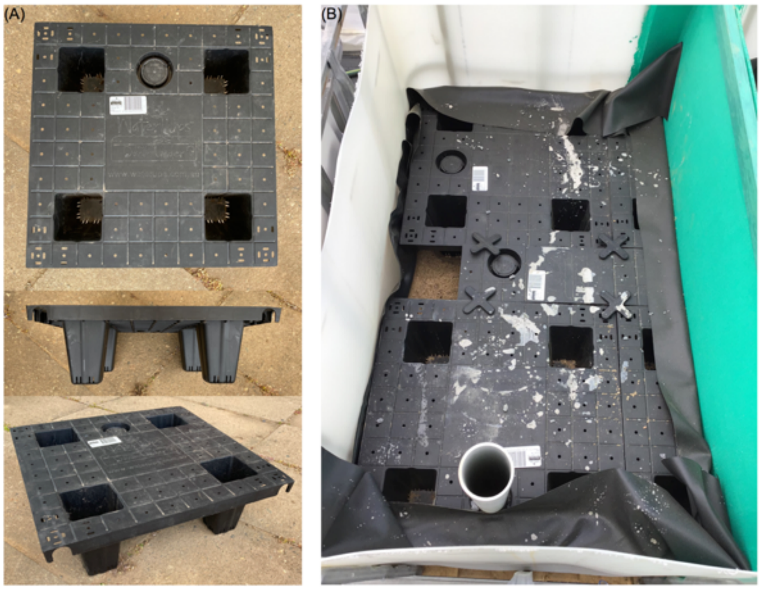

Figure 7 - (A) WaterUps® module showing hollow legs to be filled with wicking medium and top to support growing medium above water-filled reservoir. (B) WaterUps® modules placed in the bottom of a wicking bed prior to filling the legs with wicking medium.

The sixteen wicking beds were placed inside a 4 x 6m poly tunnel. Figure 8 shows the layout of the beds within the polytunnel and Figure 9 is a photo of the polytunnel.

The reservoirs of the wicking beds were filled with material to 200mm depth and the surface of the material was levelled. Water was added to the reservoir until free water was just visible on the surface of the reservoir medium and the water level was at the top of the indicator/overflow tubes on the sides of the beds.

For sand and gravel reservoirs, a layer of geotextile was placed over the reservoir material. Growing medium was added to 300mm depth on top of the reservoir layer (Figure 10).

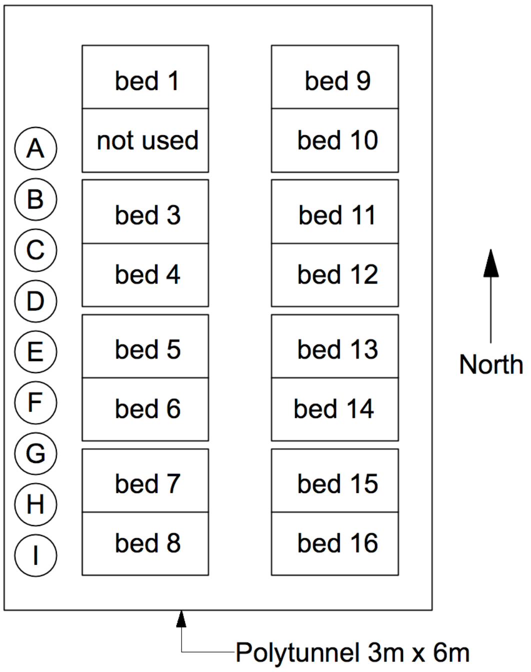

Figure 8 - Layout of wicking beds within polytunnel. Rectangular beds 1-16 used in WBT1 and WBT2. Circular beds A-I used in WBT3.

Figure 9 - Polytunnel in Bywong, NSW containing wicking beds used in this trial

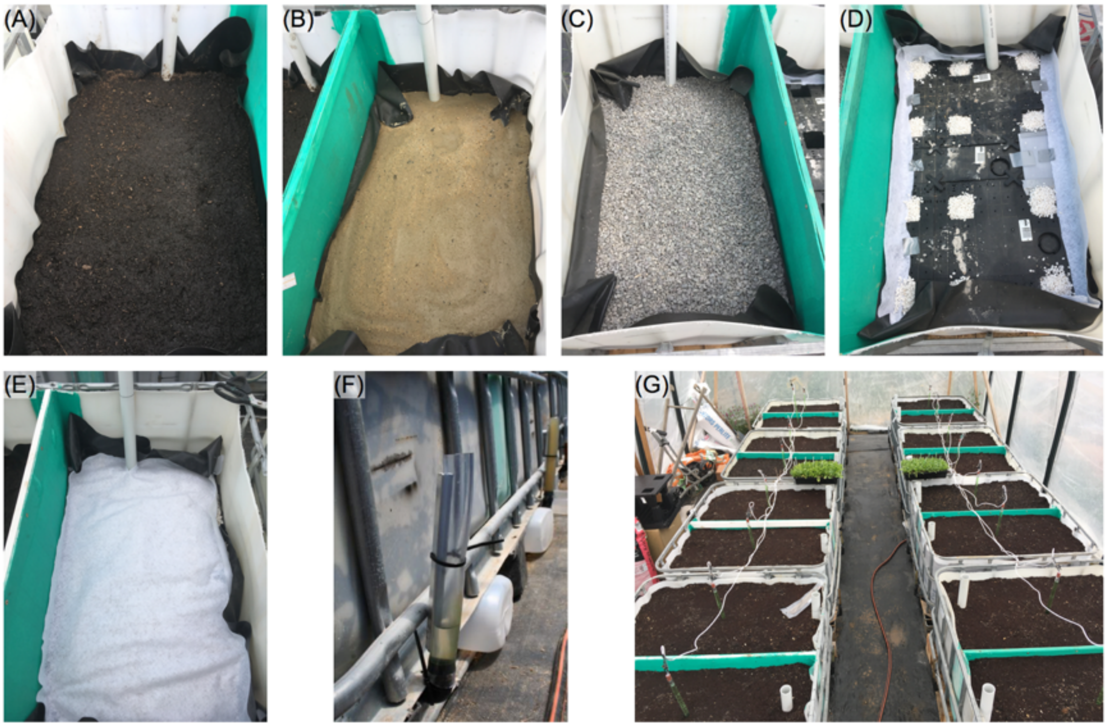

Figure 10 - IBC wicking beds for WBT1 and WBT2 during construction showing container, waterproofing pond liner, PVC fill pipe and reservoir media in place: (A) cocopeat mix, (B) sand, (C) gravel, (D) WaterUps® with perlite wicking medium. (E) Geotextile covering reservoir media prior to adding growing media. (F) Indicator tubes to show water level in reservoir. (G) Beds filled with growing media and tensiometers in place ready for planting.

The growing medium in all beds was watered from on top until the medium was saturated and water flowed out of the overflow tubes. The beds were left to equilibrate for 12 hours before planting.

For WBT1, each bed was planted with twelve spinach (*Spinacia oleracea* 'Ironman') seedlings on 17/10/2019. The seedlings were grown tightly packed in punnets and suffered some root damaged when they were separated for transplanting. After planting, each bed was watered from on top with 1.5L of dilute Seasol solution (30ml Seasol in 9L water) then another 2L water. An additional 2L/bed of water was applied in the same manner on each of the next four days. Five days after planting each bed was watered with 1.5L of dilute Powerfeed fertiliser (50ml Powerfeed in 9L water) as the seedlings did not appear to be thriving. Following this, all beds relied on capillary watering from their reservoir.

Figure 11 - WBT1 wicking beds with spinach seedling after planting

Soil water measurements were made with electronic tensiometers with their tips buried 150mm from the surface in the centre of each bed. See section 3.5 for details of the tensiometers. Measurements from the tensiometers were made manually using a regulated 5V power supply and a handheld multimeter.

Reservoir water levels were measured by the drop in the level of water in the indicator tubes on the outside of each bed. However, this was only effective for the reservoirs containing gravel or WaterUps®. Because the indicator tube showed the level of free water in the reservoir it was not an effective measure for media with a large field capacity. Once the free water was removed from the sand and cocopeat reservoirs by capillary rise, the level in the indicator tubes dropped to the bottom even though the reservoirs would have still held a considerable amount of available water.

The reservoirs were refilled between one and three times during the course of the experiment with the volume of water required to fill each reservoir recorded (Table 4).

Table 4 - Schedule of the number of days after transplant that the reservoir of the wicking beds were refilled during WBT1

Treatment	Bed	Refill (days after transplant)
cocopeat	1, 6, 10	28, 32, 42
gravel	5,14,16	42
sand.cp	3,7,11	28, 32, 42
sand.pm	4	28, 42
sand.pm	9,13	28, 32, 42
WaterUps®	8,12,15	42

Measurements of the percentage of the area of each bed covered by spinach leaves were made using the Canopeo app (Patrignani & Ochsner, 2015) on an iPhone SE. Measurements were taken until the leaf canopy covered most of the surface area of the bed, after which this method was determined not to provide an accurate measurement of plant growth.

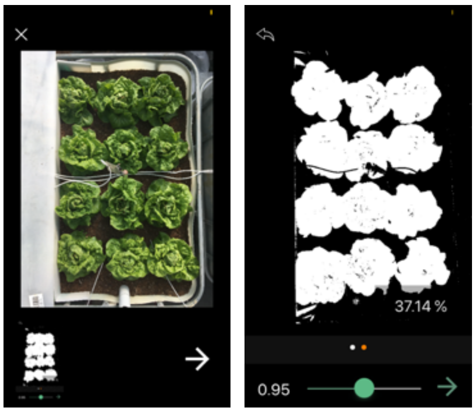

Figure 12 - Example of photo and plant area analysis by Canopeo app (photo of lettuce plants from WBT2)

The spinach plants were harvested by cutting the stems level with the top of the soil at 101 days after transplanting. By this time the plants were dead from high temperatures and were desiccated (Figure 13). The plants were regarded as air dried for the purpose of weighing. The total weight of all plants from each bed was recorded using certified commercial scales (CAS SW1C-10).

After harvest, each reservoir was refilled with water and the volume of water added was recorded.

Figure 13 - Typical bed of desiccated spinach plants prior to harvest (bed 16)

3.3.2 Wicking bed trial 2 (WBT2)

The second wicking bed experiment used the same beds and treatments as WBT1 but were planted with lettuce instead of spinach. Prior to planting, some refurbishment of the beds occurred.

In the WaterUps® beds (beds 8,12,15), perlite was removed from the legs of the WaterUps® modules and replaced with sand. This was done because, although the manufacturer recommended using perlite, the performance of the WaterUps® beds during WBT1 was less than expected and the capillary rise experiments had shown that sand was a better wicking medium than perlite.

In all beds, the growing media was dug over to return all beds to a common state. Fertiliser was added to all beds (66g/bed of Scotts Osmocote Vegetable Tomato and Herb fertiliser) and the growing media was topped up with more cocopeat mix or potting mix as appropriate.

Electronic tensiometers were reinstalled at 150mm depth in the centre of each bed. The tensiometers were connected to custom built data loggers set to record readings once per hour. The data loggers also recorded temperature and humidity near the surface of the beds in the centre of the poly tunnel. Details of the data loggers is presented in section 3.5.

Prior to planting, the reservoirs were filled and all beds were top watered until the growing medium was saturated and water overflowed from the indicator tubes. The beds were left to equilibrate for 15 hours.

Twelve butterhead lettuce seedlings (*Lactuca satvia var. capitata*) were transplanted into each bed on 20/2/2020. Seedlings were five weeks old had had been grown one per cell in an attempt to avoid the planting shock observed with the spinach seedlings in WBT1. Figure 14 is a photograph of one of the beds after transplanting the lettuce seedlings. All beds were top watered with 1.8L of water after planting, and again on days 1 and 3 after planting. Four days after planting the lettuces in potting mix (sand.pm treatment) were wilting and 2.4L of water was applied to all beds. Some of these plants were still showing signs of water stress later that day so an additional 1.8L of water was applied to the sand.pm beds only (beds 4,9,13). Following this, all beds relied on capillary watering from their reservoir.

Figure 14 - Typical planting of lettuce seedlings for WBT2 (bed 6)

The reservoirs on all beds were refilled 36 days after transplant.

Measurements of soil moisture, electrical conductivity and soil temperature were made with a Pulse™ meter (Bluelab, www.bluelab.com/pulse). Before the start of the experiment, the meter was calibrated as per the manufacturer's instructions to read 100% soil moisture in the cocopeat mix at field capacity. The same calibration was used for measuring both the cocopeat mix and the potting mix. Data from the meter was recorded on an iPhone using the Pulse™ app from Bluelab. Measurements were made at three equally spaced locations in each bed. Measurements at 50mm, 100mm and 200mm depth were made at each location.

Leaf area measurements were made using the Canopeo app as in WBT1.

Lettuces were harvested 45 days after transplant by cutting the stems level with the top of the soil. Each lettuce was weighed individually then cut in half and spread on racks in the poly tunnel for air drying. Lettuces were air dried for 36 days then the total dry weight for each bed was recorded.

3.3.3 Wicking bed trial 3 (WBT3)

The aim of WBT3 was to investigate the effect of a geotextile layer on the movement of water within a wicking bed. Three treatments were used:

cp.gtex	cocopeat mix in both the reservoir and growing layers, but separated by a geotextile membrane
cp.none	cocopeat mix in both the reservoir and growing layers with no geotextile (equivalent to the cocopeat treatment in WBT1 and WBT2
sand.none	washed sand in the reservoir layer and cocopeat mix in the growing layer, with no geotextile separating the layers

The cocopeat mix was the same as the earlier experiments (6:3:1 cocopeat fibre, municipal green waste compost, washed sand plus additional fertiliser). The sand and geotextile were also the same as used in the earlier experiments.

Three replicates of each treatment were used.

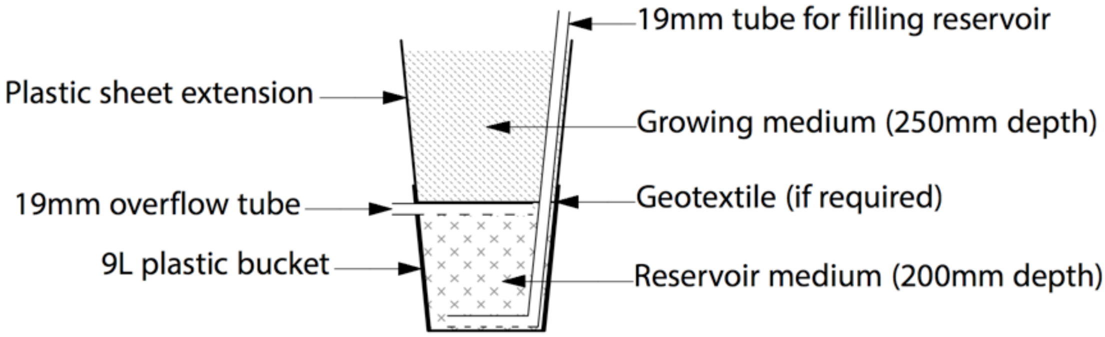

Figure 15 - Design of wicking beds based on 9L plastic buckets used for WBT3

The wicking beds for WBT3 were constructed using 9L plastic buckets with extensions of 600mm wide plastic damp course material to give a total depth of 500mm. Overflow drainage for the reservoir layer was provided by 19mm diameter plastic pipe through the sides of the buckets 200mm up from the base. A 19mm plastic pipe to the bottom of the bucket was used to fill the reservoir with water (Figure 15 and Figure 16). The nine wicking beds for WBT3 were placed randomly in a single row along the western side of the same polytunnel used for WBT1 and WBT2 (Figure 8).

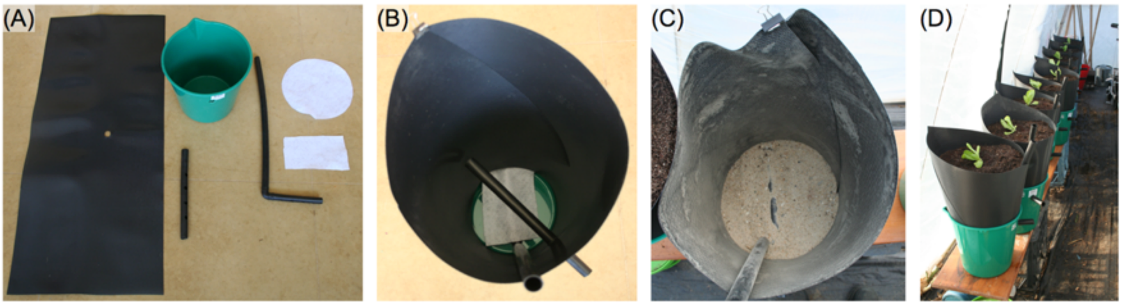

Figure 16 - Wicking beds for WBT3 during construction. (A) components: bucket, plastic dampcourse, overflow and fill pipes, geotextile. (B) Assembled wicking bed with fill pipe covered with geotextile and overflow pipe. (C) Wicking bed with sand in reservoir. For treatment with geotextile, a circle of geotextile would have been placed on top of the sand. (D) Filled and planted wicking beds in the polytunnel.

Prior to planting, the reservoirs of the beds were filled and the beds top watered until the reservoirs overflowed. The beds were allowed to drain for three hours. One five week old lettuce seedling (*Lactuca satvia var. capitata*) was planted in each bed on 26/2/2020. Beds were top watered with 150ml/bed of water and another 150ml/bed was applied two days after planting. Following this, all beds relied on capillary watering from their reservoir.

Soil moisture measurements were made with the same Pulse^{TM} meter used in WBT2.

Water was added to all beds until the reservoirs overflowed 34 days after transplanting. The lettuce plants were harvested 44 days after transplanting by cutting the stems level with the surface of the soil. The harvest (wet) weight of each lettuce was recorded. The reservoirs of each bed were refilled after harvest and the beds were top-watered until the reservoirs overflowed. The amounts of water added to the reservoirs and growing media were recorded.

3.4 Data analysis

All data was recorded in Microsoft Excel spreadsheets. Some data was also stored in a MySQL database which was used to extract subsets of the data for analysis. Analysis of variance was performed using R version 3.5.2 (https://www.r-project.org). Means were separated by Tuckey's HSD test with $P \leq 0.05$ considered to be statistically significant.

3.5 Electronic tensiometers and data logger

Electronic tensiometers (Figure 17) and Arduino based data loggers were constructed based on a method described by Thalheimer (2013). The ceramic tips used were part of the Blumat® Classic pot plant watering system obtained from Eurolux Australia.

Figure 17 - Electronic tensiometer used for WBT1 and WBT2

Two data loggers that recorded readings from eight tensiometers plus temperature and humidity were constructed. The parts used in the data loggers are listed in Table 5 and shown in Figure 18. The Arduino code running on the data loggers is available in appendix 2.

Table 5 - Components used in data logger for tensiometer, temperature and humidity data

Function	Component used
Microcontroller board	Arduino Nano V3 with ATmega328
SD card and real time clock module	Geekcreit Nano V3.0 Data Logging Shield
Multiplexor chip	74HC4067 High Speed CMOS 16-Channel Analog Multiplexer/Demultiplexer
Temperature and humidity sensor	Duinotech Temperature and Humidity Sensor Module Jaycar cat no XC4520

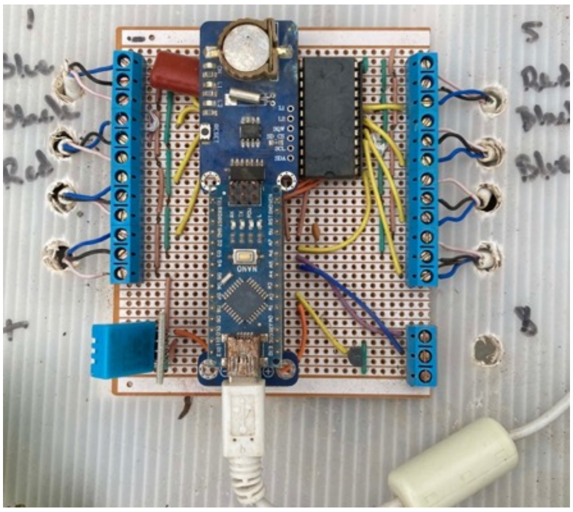

Figure 18 - Arduino-based data logger used for WBT2

4 RESULTS

This chapter presents the results obtained from each of the five experiments conducted as part of this study (water holding capacity, capillary rise and three wicking bed trials). The results of each experiment are presented separately. Comparisons between experiments and the conclusions that can be drawn from these results are contained in the discussion in chapter 5.

4.1 Water holding capacity of potential reservoir media

The main function of the reservoir layer in a wicking bed is to store water and supply it to the growing medium above. A greater volume of stored water (provided the reservoir can supply it via capillary rise) means longer periods between refill of the reservoir and therefore less work in maintaining the crop growing in the wicking bed. Water is held in pore spaces between solid particles of the reservoir medium; thus water holding capacity is effectively a measure of the porosity of the medium. Table 6 presents the volume of water (mean of three replicates) that could be added to a 670ml test container filled with reservoir media.

Table 6 - Total volume of water to fill 670ml test container filled with reservoir material and volume of water remaining in container after drainage (as field capacity)

Material	Saturated capacity (ml)			Field capacity (ml)		
	mean		s.d.	mean		s.d.
cocopeat mix	476	d[1]	11.00	431	d	12.02
crushed gravel	328	c	16.52	53	a	14.57
crusher dust	226	a	33.45	207	b	17.90
river gravel	264	ab	11.93	59	a	2.52
river sand	266	ab	4.51	251	c	7.55
scoria	321	c	8.08	67	a	4.00
washed sand	273	b	14.01	198	b	9.45
significance	P= $9.32e^{-10}$			P= $2.7e^{-15}$		

(1)Mean separation within columns by Tukey ($P<0.05$)

The cocopeat mix contained the most water (476ml or 64% by volume) followed by crushed gravel (328ml or 49%), significantly more than any other medium except scoria. The least water was held by crusher dust (226ml), followed by river gravel and river sand.

The media with smaller particles (cocopeat mix, sands, crusher dust) retained more water when the free water was drained away than the coarser media (presented as field capacity in Table 6). The cocopeat mix retained the most water due to the cocopeat fibres being able to absorb water (Ilahi & Ahmad, 2017) as well as water being retained in pores between the particles. Of the inorganic materials, river sand retained significantly more water than the other media. Crusher dust and washed sand retained more water than any of the coarser media (crushed gravel, river gravel and scoria).

4.2 Reservoir capacity of wicking beds

After the reservoir medium was placed in the wicking beds used for WBT1 and WBT2 to a depth of 200mm, the reservoirs were filled with water (Table 7). The reservoir with the WaterUps® product held significantly more water (72.6L) than any other reservoir. This was 65% of the nominal reservoir volume. Sand filled reservoirs held the least water (27.6 and 26.6L) or approximately 25% of the nominal reservoir volume. There was no significant difference between the amount of water held in the cocopeat reservoir(47.2L) and the gravel reservoir (51.3L).

Table 7 - Volume of water required to fill reservoir layer of wicking beds used in WBT1 and WBT2, predicted volume based on experimental results of media water capacity and difference between predicted and actual volume

Treatment	Water capacity (L)				
	Actual mean		s.d.	Predicted[2]	Difference (predicted-actual)
cocopeat	47.2	b[1]	7.39	78.2	31.0
gravel	51.3	b	1.30	53.9	2.6
sand.cp	26.6	a	3.04	44.9	17.8
sand.pm	27.6	a	1.66	44.9	16.8
WaterUps®	72.6	c	1.57	65.1	-7.5
significance	P= 0.000000183				

(1)Mean separation within column by Tukey (P<0.05)

(2)Predicted water capacity for cocopeat mix, sand and gravel was based on experimental saturated capacity results in Table 6. Predicted capacity for WaterUps® was calculated from the physical dimensions of the product and does not include an allowance for water that could be contained within the material filling the legs of the WaterUps® or the sand base they were standing on.

Table 7 also shows the predicted water capacity for each reservoir based on the experimental results in Table 6. The capacity of reservoirs filled with crushed gravel (46% of nominal volume) was reasonably close to the predicted volume based on the measured saturated capacity (49%) but the actual water capacity of reservoirs filled with cocopeat mix and sand was much less than predicted (43 and 24% compared with 71 and 41%. It is likely that more compaction occurred when placing the cocopeat mix and sand in the wicking beds than when the experimental containers were filled. Compaction would reduce the pore space available for holding water. The gravel would compress less than sand or cocopeat mix so the difference between the wicking beds and the experimental containers would be smaller and this is reflected in the closeness of the predicted and actual water capacity. The actual capacity of

WaterUps® wicking beds was greater than predicted, but the predictions did not include an allowance for water in the wicking material (perlite) in the hollow legs of the WaterUps®, or the sand bed that the WaterUps® were placed on.

4.3 Capillary rise in reservoir materials

Water in the reservoir layer of a wicking bed must be delivered to the growing layer for it to be used by the plants. Capillary rise through the reservoir medium is the mechanism that provides this water delivery. If water cannot rise by capillary action through the full depth of the reservoir, then not all water in the reservoir can be used.

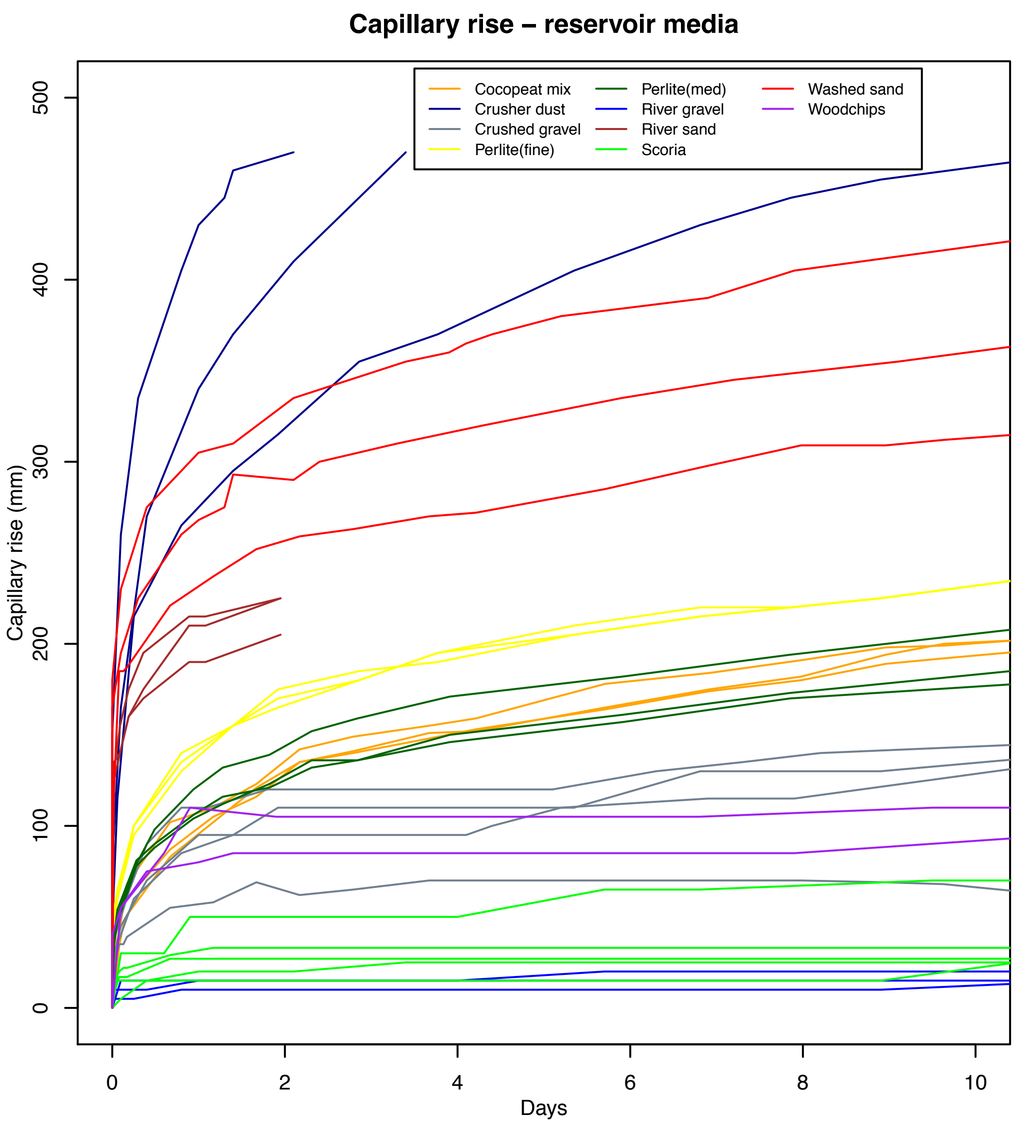

Figure 19 - Capillary rise of water above free water level in 50mm diameter perspex tubes filled with potential reservoir media. The first measurement was taken half an hour after placing the base of the tubes in water, subsequent measurements taken at increasing intervals from two hours to approximately daily.

The capillary rise of water through various media that could be used in the reservoir layer was assessed using 50mm diameter Perspex tubes. Three replicates were performed for each material except woodchips (2 replicates), scoria (5 replicates) and crushed gravel (4 replicates). The greatest capillary rise was obtained in the crusher dust (Figure 19) with two of the three replicates rising to the top of the tubes (470mm) within three days and the third replicate reaching this level within 11 days.

Crushed gravel, river gravel, scoria and woodchips all failed to provide a capillary rise greater than 200mm (Table 8). The cocopeat mix had an mean maximum capillary rise of 198mm.

Not all samples in the capillary rise experiments had readings taken at exactly 10 days. The 10 day rise shown in Table 8 has been estimated by assuming a constant rise between reading taken before 10 days and the one after 10 days and calculating the proportion of that rise from reading before 10 days (Equation 5).

$$R_{10} = R_- + (R_+ - R_-) * (10 - D_-) / (D_+ - D_-) \qquad (5)$$

where R_{10} is the calculated rise after 10 days, R_- is the rise recorded before 10 days, R_+ is the rise recorded after 10 days, D_- is the number of days since the start of the experiment when the reading before 10 days was taken and D_+ is the number of days when the reading after 10 days was taken.

Table 8 - Maximum capillary rise above free water in 50mm diameter Perspex tubes filled with potential reservoir media after 10 days

Material	**Maximum rise (mm)**		
	mean		**s.d.**
cocopeat mix	198	de[1]	3.79
crushed gravel	118	c	35.44
crusher dust	467	g	4.62
perlite(fine)	232	e	0.00
perlite(med)	188	de	15.70
potting mix	165	cd	5.77
river gravel	17	a	2.89
river sand	218	de	11.55
scoria	35	ab	19.76
washed sand	364	f	52.56
woodchips	101	bc	12.73
significance	P <2e^{-16}		

(1)Mean separation within column by Tukey (P<0.05)

The measurement of capillary rise in river sand was terminated after two days because it was apparent that it was not showing a greater rise than the washed sand and that the washed sand would be a better candidate for use in wicking bed trials. The maximum rise measured for river sand (218mm) was after 1.95 days. The mean capillary rise for washed sand after 1.95 days was 292mm which is significantly more (p=0.029) than the rise in river sand after this time.

To give an indication of the comparative rate of rise between media, the number of days taken to reach 100 and 200mm are presented in Table 9. In general, the materials that had a higher total rise also had a faster rate of rise.

Table 9 - Number of days for capillary rise in reservoir media in 50mm Perspex tubes to reach 100mm and 200mm above free water

Medium	Days to rise to 100mm			Days to rise to 200mm		
	mean		s.d.	mean		s.d.
Cocopeat	0.93	ab[1]	0.26	10.98	c	1.88
Crushed gravel	2.20	b	1.96			
Crusher dust	0.05	a	0.00	0.10	a	0.06
Perlite (fine)	0.28	ab	0.05	5.66	b	0.63
Perlite (med)	0.71	ab	0.16			
River sand	0.01	a	0.00	0.96	a	0.74
Washed sand	0.02	a	0.01	0.13	a	0.10
significance	P=0.0289			P=0.000000204		

(1)Mean separation within columns by Tukey (P<0.05)

A capillary rise rate of 5mm.day^{-1} has been suggested as a minimum for subirrigation (Schindler, Lischeid, & Müller, 2017). Table 10 shows the maximum height at which each of the materials tested were able to maintain this rate of rise. There is a direct correlation between this height and the maximum height over 10 days.

Table 10 - Maximum capillary rise above free water in reservoir media in 50mm Perspex tubes with rate of rise > 5mm.day^{-1}

Medium	Maximum height (mm)		
	mean		s.d.
Cocopeat mix	199	d[1]	7.55
Crushed gravel	114	bc	31.50
Crusher dust	470	f	0.00
Perlite(fine)	252	d	4.61
Perlite(med)	190	cd	18.23
River gravel	10	a	5.00
River sand	239	d	45.39
Scoria	27	a	14.65
Washed sand	368	e	69.76
Woodchips	96	ab	14.85
significance	9.06e-14		

(1)Mean separation within column by Tukey (P<0.05)

The maximum reservoir capacity for each material is a reservoir that is as deep as the maximum height to which the medium can sustain a capillary rise of 5mm per day. This criteria has been used to calculate the maximum reservoir capacity for several materials (Table 11).

Table 11 - Maximum reservoir depth, water capacity and days of supply for reservoir medium to provide capillary flow of 5mm.d^{-1} from the full depth of the reservoir

Medium	Reservoir depth (mm)	Reservoir capacity (Litres.m^{-2})	Days of supply
Cocopeat mix	199	141	28
Crushed gravel	114	56	11
Crusher dust	470	159	32
River gravel	10	4	1
River sand	239	95	19
Scoria	27	13	3
Washed sand	368	150	30

4.4 Capillary rise in growing media

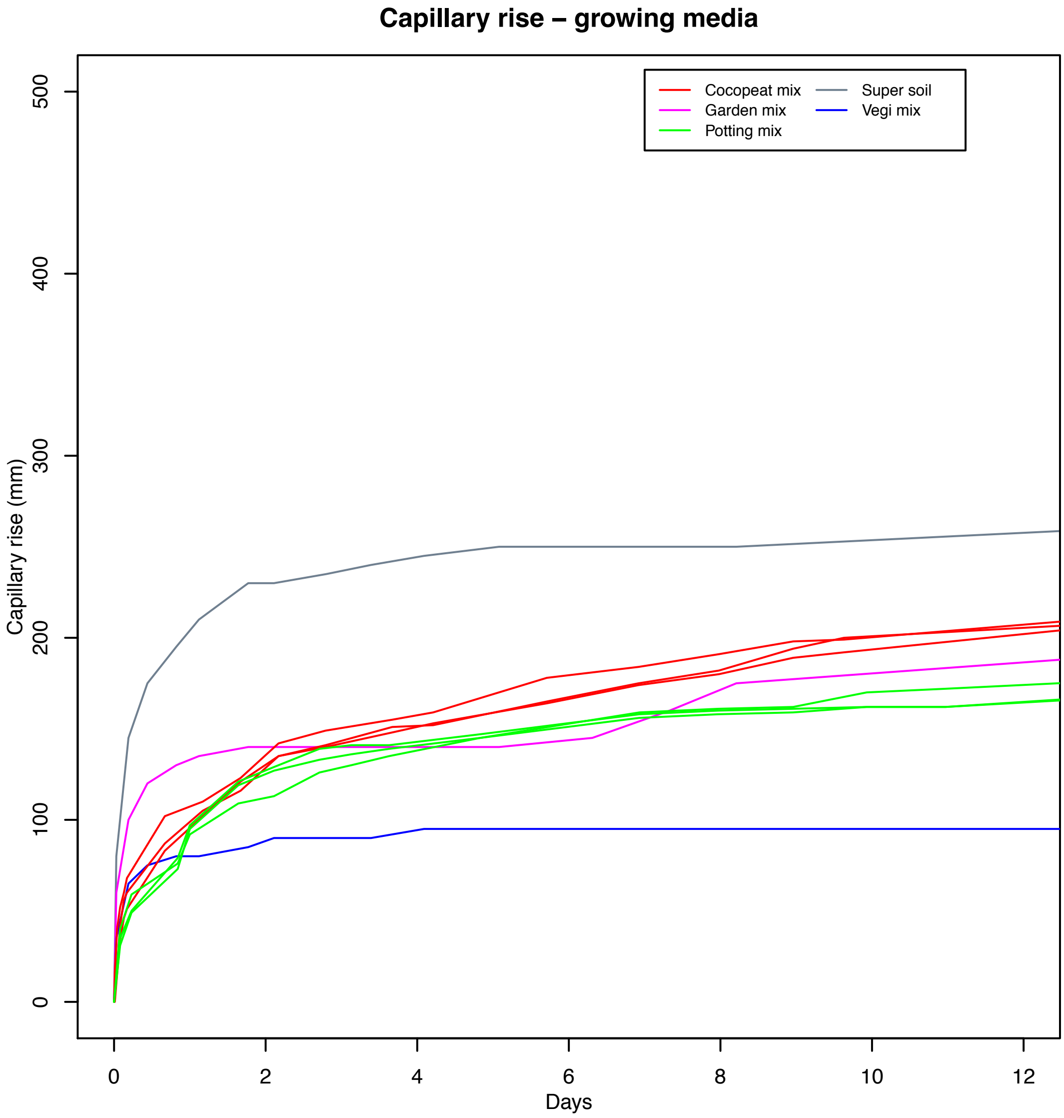

Figure 20 - Capillary rise of water above free water level in 50mm diameter Perspex tubes filled with potential growing media. The first measurement was taken half an hour after placing the base of the tubes in water, subsequent measurements taken at increasing intervals from two hours to approximately daily.

Capillary rise was also tested in a selection of potential growing media. This included three soils from a local landscape supplier, the cocopeat mix that was also included in the reservoir materials results above, and a commercial potting mix (Figure 20). Three replicates were done for the cocopeat mix and potting mix. Only one replication was done with each of the soils because it appeared that large particles of undecomposed bark or woodchip caused air gaps in the media in the plastic tubes. These air gaps would stop capillary rise and the results may not be representative of these materials in actual use in wicking beds.

Despite potential problems with hydrophobicity, the cocopeat mix had a significantly greater maximum capillary rise than the potting mix. The maximum level reached in ten days for each media is shown in Table 12 and the maximum height reached with a rise greater than 5mm per day is in Table 13.

Table 12 - Maximum capillary rise above free water in 50mm diameter Perspex tubes filled with potential growing media after 10 days

Media	Maximum capillary rise (mm)		
	mean		s.d.
cocopeat mix	198	a[1]	3.79
potting mix	165	b	5.77
significance	P= 0.00116		

(1)Mean separation within column by Tukey (P<0.05)

Table 13 - Maximum capillary rise above free water in reservoir media in 50mm Perspex tubes with rate of rise > 5mm.day^{-1}

Medium	Max height (mm)		
	mean		s.d.
cocopeat mix	199	a[1]	7.55
potting mix	162	b	8.14
significance	P=0.00433		

(1)Mean separation within column by Tukey (P<0.05)

4.5 Wicking bed trial 1 (WBT1) - Spinach

This section presents results from the first wicking bed trial growing spinach in IBC wicking beds. Results collated include the dry weight of plants, volume of water used, soil moisture measurements and reservoir water levels. Three replicates of each treatment were used.

4.5.1 Plant weight

The spinach plants were harvested 101 days after transplanting into the wicking beds. During the month starting 45 days after planting, there were 11 days with maximum temperatures above 35^{o}C (BOM, 2020) and all the plants had died and were largely desiccated by day 72. Spinach is a cool season crop and is intolerant of temperatures above 25^{o}C (Swiader & Ware, 2002). Plants were harvested 101 days after transplant.

All plants in all beds were in the same condition and the weight of the plants as harvested was used as the dry weight in Table 14. The greatest weight (236g) was in both the cocopeat and sand.cp beds and the least plant weight (116g) was in the sand.pm treatment.

Table 14 - Total dry weight per bed of stems and leaves of spinach stems and leaves (12 plants per bed) in WBT1 harvested in a desiccated state 101 days after transplant

Treatment	Dry plant weight (g)		
	mean		s.d.
cocopeat	472	b[1]	117.01
gravel	310	ab	40.77
sand.cp	472	b	19.47
sand.pm	232	a	66.76
WaterUps®	392	ab	29.55
significance	P= 0.00404		

(1)Mean separation within column by Tukey ($P<0.05$)

Visually, there appeared to be differences in plant growth between the halves of the beds next to the aisle in the poly tunnel and the halves on the outer edges of the poly tunnel (Figure 21). The reasons for this variation are unclear. It affected both the eastern and western sides of the polytunnel. It may have been due to proximity to the polytunnel walls, but the beds were not centred in the polytunnel and the inner half of the eastern beds was the same distance from the polytunnel wall as the outer half of the western beds. One possible explanation is that the seedlings on the outer halves of the bed suffered more trauma during transplanting than the seedlings on the inner half. All seedlings were planted from the isle in the centre of the polytunnel so planting the outer half involved reaching further to place the seedlings in the soil.

Figure 21 - Photo of one bed in WBT1 showing apparent difference in growth between plants next to the centre (left of picture) and the wall of the polytunnel (right)

To investigate any possible effects of these growth differences, after harvest the plants from each bed were weighed in two portions; those from the inside half and those from the outside half. The weight of plants from all treatments from the inner halves of the beds was significantly greater than the weight from the outer halves (P=0.0463, Table 15), but there was no interaction between the effects of position and reservoir treatment.

Table 15 - Total dry weight of stems and leaves of spinach plants from inner and outer halves of all beds in WBT1 harvested in a desiccated state 101 days after transplant

Position	Dry plant weight (g)		
	mean		s.d.
in	215	a[1]	79.04
out	160	b	62.75
significance	P=0.0463		

(1)Mean separation within column by Tukey (P<0.05)

4.5.2 Water use

Water was added to the reservoirs of the wicking beds several times during the experiment. After harvesting the plants the reservoirs were again filled. The total amount of water added to each bed is shown in Table 16. There were significant differences between the total water added to each treatment. The cocopeat reservoir took the most water (105L) and the gravel just more than half this amount (56.7L). The amount of water added to the reservoir does not represent the total evapotranspiration from the beds because the experiment was started with the growing medium in the beds at field capacity but the growing medium was not re-wet after harvest and contained less moisture than field capacity. This shortcoming was addressed in WBT2 when the volume of water needed to re-saturate the growing medium was also measured.

Table 16 - Total volume of water added to each bed in WBT1 during growing period plus amount needed to refill reservoir after harvest

Reservoir treatment	Water added (L) mean		s.d.
cocopeat	105.0	c[1]	16.82
gravel	56.7	a	6.81
sand.cp	92.0	bc	5.20
sand.pm	64.3	ab	17.21
WaterUps®	77.7	ac	5.51
significance	P=0.00286		

(1)Mean separation within column by Tukey (P<0.05)

There was a reasonable positive correlation (r^2=0.7061) between the amount of water used in each bed and the dry weight of plants from that bed (Figure 22).

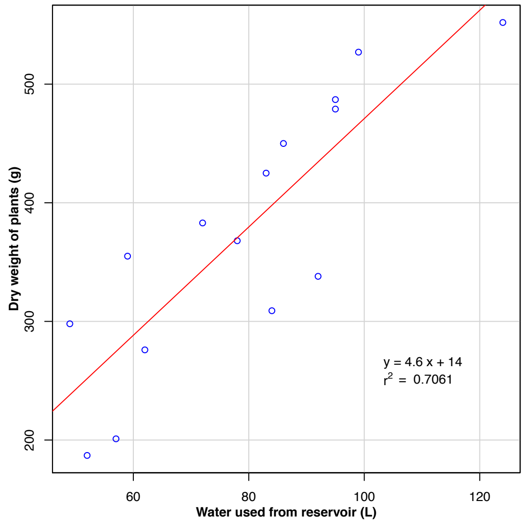

Figure 22 - Correlation by bed between total dry plant weight and volume of water used to refill reservoir for all treatments in WBT1

Plant water use (WU) and water use efficiency (WUE) were calculated using equations 6 and 7 respectively, and results are shown in Table 17.

$$WU = I/Y \qquad (6)$$

$$WUE = Y/I \qquad (7)$$

where I is the volume of water added to the reservoir during the experiment and Y is the dry weight of the spinach plants.

Table 17 - Water use and water use efficiency (WUE) of growing spinach in WBT1. Calculated from total dry weight of plants per bed and total water added to reservoirs during the experiment

Treatment	Dry weight			
	Water use (L/kg)		WUE (g/L)	
	mean	s.d.	mean	s.d.
cocopeat	228.2 ab[1]	42.27	4.5 ab	0.80
gravel	185.1 a	34.25	5.5 b	0.90
sand.cp	194.8 a	3.61	5.1 b	0.10
sand.pm	277.8 b	5.90	3.6 a	0.10
WaterUps®	198.4 a	12.30	5.0 ab	0.31
significance	P=0.00672		P=0.0148	

(1)Mean separation within column by Tukey (P<0.05)

4.5.3 Soil moisture

Soil moisture was measured during this experiment by one tensiometer in the centre of each bed. Most beds with cocopeat, sand.cp and sand.pm were refilled on days 28 and 32 and all beds were refilled on day 42. Tensiometer readings were taken approximately every two days until day 44 and a final reading was taken on day 72. As noted in above, the plants were dead by this stage so they were using no more water

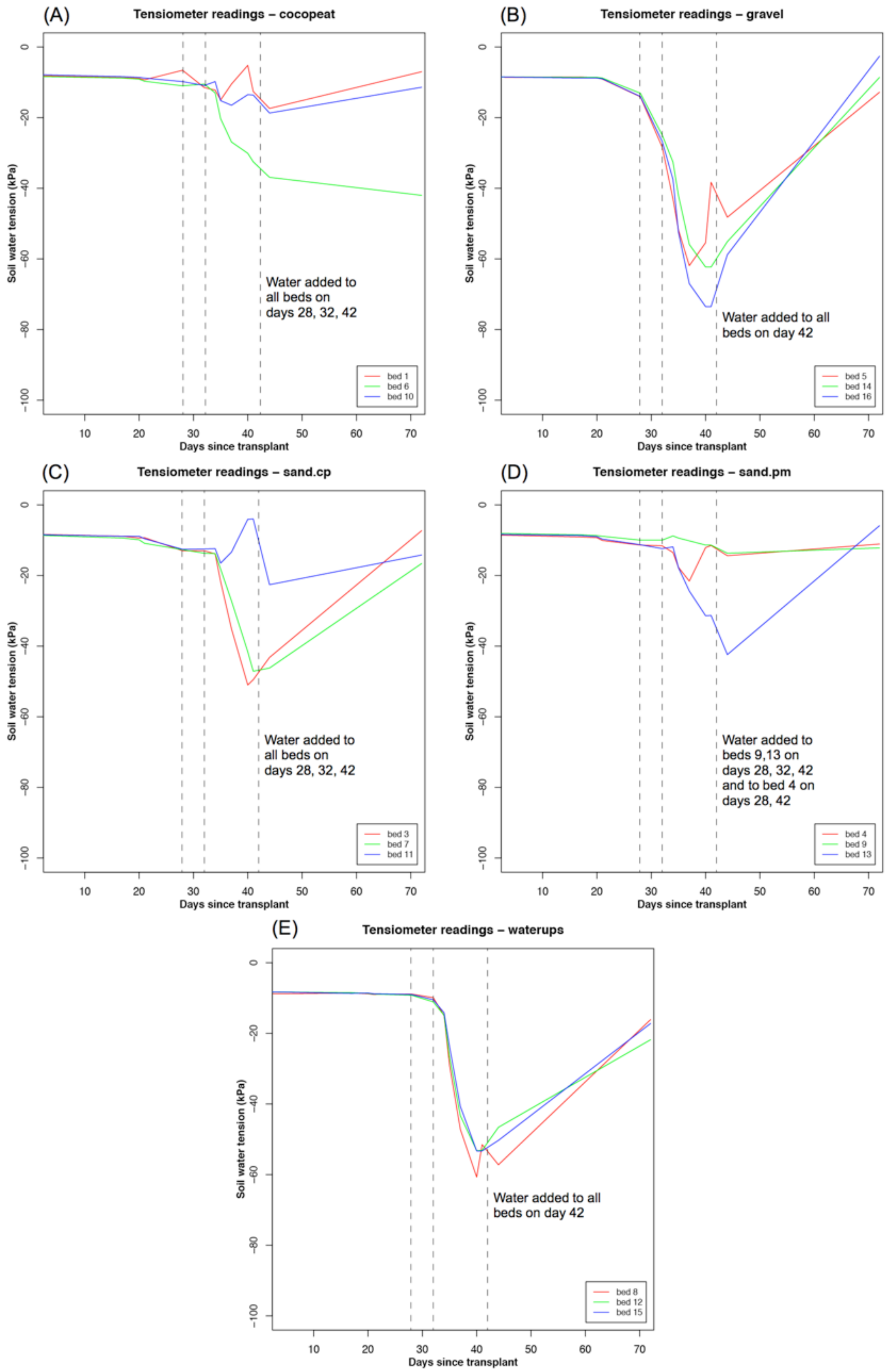

Figure 23 - Soil water tension for each wicking bed in WBT1 for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps® from tensiometers placed 150mm below the surface of the growing medium. Days when water was added to reservoirs indicated by vertical dashed lines. Tensiometer readings were taken on days 1 and 3, then at an average interval of 3 days. No readings were taken between 44 and 72 days after transplant so the shapes of the graphs during this period may not reflect actual soil water tension in this period.

but when water use stopped was not measured. Over time, the soil water tension in all treatments increased then decreased when the reservoirs were refilled.

Figure 23 shows the soil water tension measured by the tensiometers in all beds. There are a few anomalous spikes in the tensiometer readings. High readings for beds 1 (cocopeat) and 11 (sand.cp) around day 40 may be due to air leakage into the tensiometers and the tensiometers were refilled with water. Other sudden, temporary changes in soil water tension (bed 5 day 41, bed 4 day 38, bed 8 day 41) cannot be explained, but may be instrument errors rather than real soil moisture changes because the soil moisture was unlikely to change so rapidly in isolated beds.

On each day that tensiometer measurements were taken after day 3, there were significant differences in the mean measurement between treatments (Figure 24). There was greater consistency between beds in the WaterUps® treatment with the variance between WaterUps® beds being smaller than other treatments on all days except two.

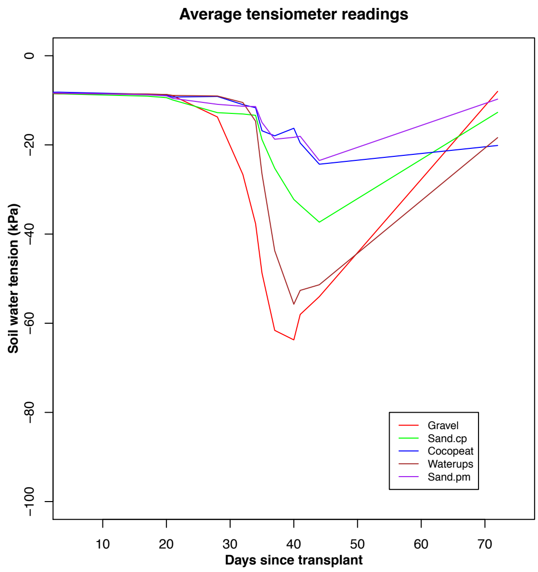

Figure 24 - Mean soil water tension by treatment in wicking beds in WBT1 from one tensiometer in centre of bed 150mm below soil surface. Tensiometer readings were taken on days 1 and 3, then at an average interval of 3 days. No readings were taken between 44 and 72 days after transplant so the shapes of the graphs during this period may not reflect actual soil water tension in this period.

There were significant differences in the maximum soil water tension between treatments (Table 18). The soil in the wicking beds with gravel reservoirs dried out the most (-65.9kPa) but this was not significantly drier than WaterUps® (-55.7kPa) or sand.cp (-40.2kPa). There was no significant difference between treatments in the minimum soil water tension.

Table 18 - Minimum and maximum soil water tension in wicking beds in WBT1 from one tensiometer in centre of bed 150mm below soil surface

Treatment	Minimum soil water tension (kPa)			Maximum soil water tension (kPa)		
	mean		s.d.	mean		s.d.
cocopeat	-26.0	b[1]	13.84	-7.1	a	1.70
gravel	-65.9	a	6.58	-6.5	a	3.38
sand.cp	-40.2	ab	15.39	-6.6	a	2.37
sand.pm	-25.9	b	14.83	-7.5	a	1.44
WaterUps®	-55.7	ab	4.30	-8.3	a	0.23
significance	P=0.00678					

(1)Mean separation within column by Tukey (P<0.05)

4.5.4 Reservoir water levels

The drop in the level of free water in the reservoir was measured on the indicator tube on the side of each wicking bed. Figure 25 shows the change in water level over time for each bed. The lowest water level reached during the experiment is shown in Table 19. As the reservoirs are 200mm deep, a drop of 200mm indicates that there is no free water in the reservoir. However, because cocopeat and sand can retain a large volume of water when free water is drained out a 200mm drop does not mean there is no water in the reservoir available to wick up into the growing media.

Table 19 - Mean maximum drop in level of free water from full level in 200mm deep reservoir layer of wicking beds in WBT1

Treatment	Water level drop (mm)	
	mean	s.d.
cocopeat	200	0
gravel	133	20.21
sand.cp	200	0
sand.pm	200	0
WaterUps®	164	51.87

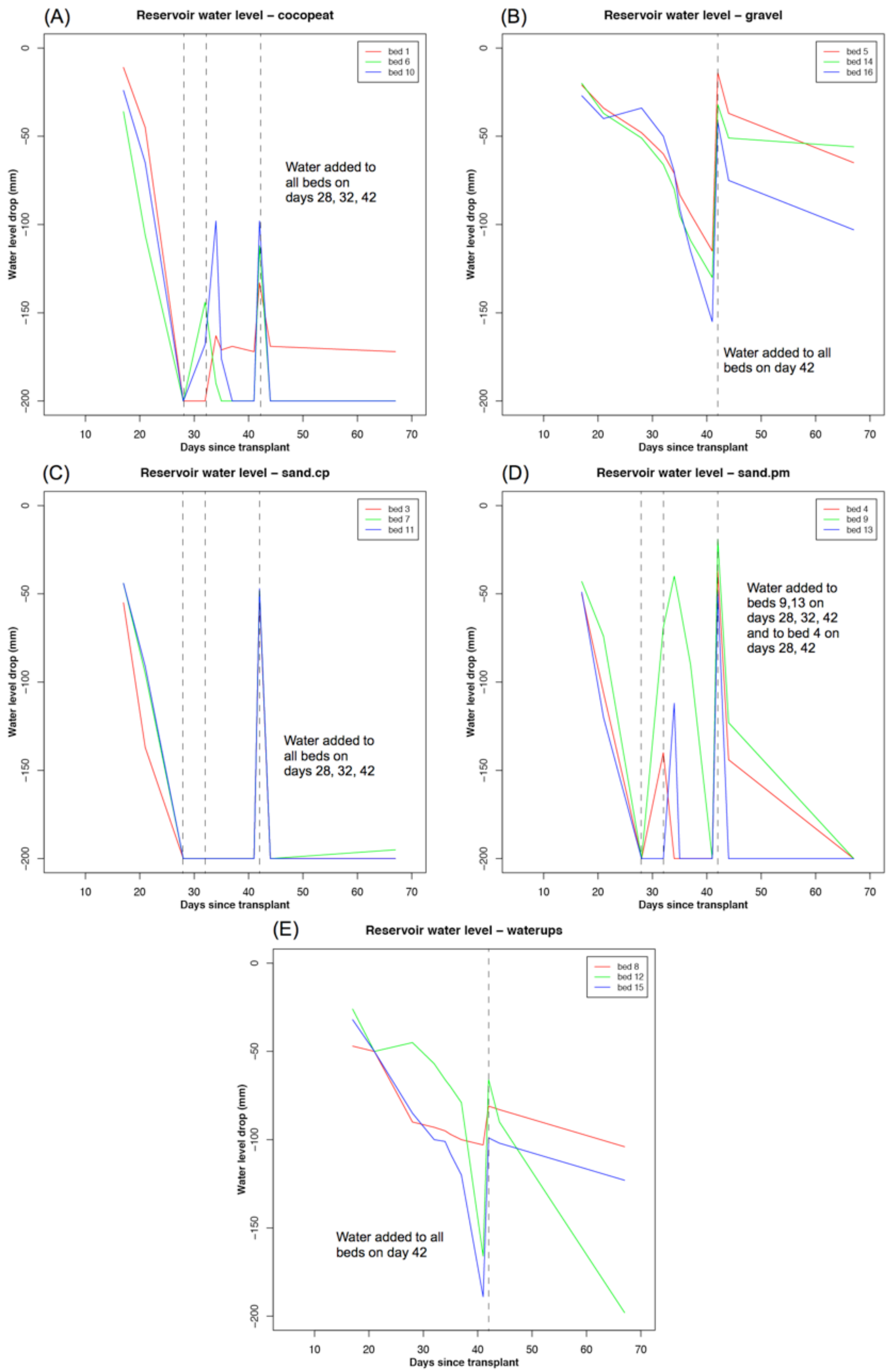

Figure 25 - Level of water over course of the experiment in indicator tube of 200mm deep reservoir of each bed in WBT1 for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps®, where 0=reservoir full and -200=no free water in reservoir. Measurements made on day 17 then an average of every 3 days until day 44 then on day 67.

4.5.5 Plant canopy area

Figure 26 - Photos showing spinach plant growth in bed 3 (sand.cp treatment) of WBT1 on days 21, 28 and 34 after transplanting

Beds were photographed using the Canopeo app (Figure 26) and the percentage of the surface area of each bed covered by leaves was recorded on days 21, 28 and 32 after transplant(Figure 27 and Table 20).

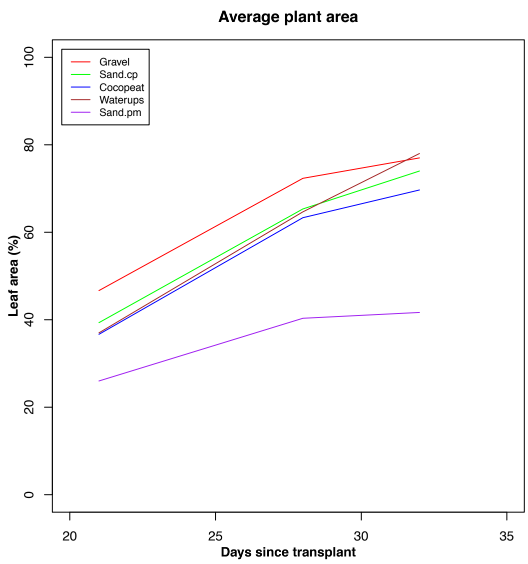

Figure 27 - Mean percentage of bed surface area covered by leaves by treatment in WBT1. Measured using Canopeo app on days 21, 28 and 32 after transplant

Twenty one days after transplanting the gravel treatment had the greatest leaf area and sand.pm the smallest. On days 28 and 32, sand.pm still had the smallest leaf area but there was no significant difference between any of the other treatments (Table 20).

Table 20 - Mean percentage of bed surface area covered by plant leaves by treatment in WBT1 on 21, 28 and 32 days after transplanting. Measured using Canopeo app

Treatment	Plant area (%) Day 21			Plant area (%) Day 28			Plant area (%) Day 32		
	mean		s.d.	mean		s.d.	mean		s.d.
cocopeat	37	b(1)	2.98	64	b	5.00	70	b	3.22
gravel	47	c	1.67	72	b	7.81	77	b	12.53
sand.cp	39	bc	5.60	65	b	1.35	74	b	4.22
sand.pm	26	a	3.26	40	a	7.95	42	a	11.76
WaterUps®	37	bc	3.66	65	b	3.74	78	b	4.10
significance	P=0.000735			P=0.000483			P=0.00156		

(1)Mean separation within column by Tukey ($P<0.05$)

4.6 Wicking bed trial 2 (WBT2) - Lettuce

WBT2 used the same wicking beds and treatments as WBT1 but grew lettuce instead of spinach. The same measurements were made (dry weight of plants, volume of water used, soil moisture measurements and reservoir water levels) plus additional measurements of wet plant weight, soil moisture, EC and temperature at three depths, and air temperature and humidity during the experiment. Three replicates of each treatment were used.

4.6.1 Plant weight

The total plant weight per bed at harvest (wet weight) and weight after air drying for 36 days (dry weight) are shown in Table 21. There was no significant variation across treatments in either wet or dry weights. Although the lettuce were air dried and not oven dried, the dry matter percentage recorded is similar to results from Montesano, Van Iersel, and Parente (2016) who obtained lettuce dry matter percentages of 4.58-5.67%.

Table 21 - Total wet and dry weight and dry matter as a percentage of wet weight per bed of lettuce stems and leaves (12 plants per bed) from WBT2. Wet weight is at harvest 45 days after transplant; dry weight is after air drying for 36 days

Treatment	Wet weight (g)			Dry weight (g)			% dry matter
	mean		s.d.	mean		s.d.	
cocopeat	5761	a1	489.28	240	a	9.61	4.17%
gravel	5696	a	784.23	232	a	26.76	4.07%
sand.cp	5856	a	49.12	244	a	20.60	4.17%
sand.pm	5780	a	286.11	248	a	4.04	4.29%
WaterUps®	6116	a	311.85	210	a	14.01	3.43%
significance	not significant			not significant			

(1)Mean separation within column by Tukey ($P<0.05$)

Because of a variation in soil moisture within beds had been found, each lettuce was weighed individually. However, there was no significant difference in the weight of individual lettuces within beds.

4.6.2 Water use

At the time of transplant, the reservoirs of all beds were full and the growing medium was at field capacity. Table 22 shows the total amount of water added to the reservoir of each bed during the growing period plus the water needed to refill the reservoir after harvest and to return the growing media to field capacity. This gives the total amount of water lost from the beds by evapotranspiration during the growing period. The total amount of water added to the reservoir (excluding the rehydration of the growing media) is included for comparison with results from WBT1 where the growing media were not rehydrated after harvest. There was no difference in the significance of the comparisons between treatments when the rehydrating water was included.

Table 22 - Total water added per bed including additions to reservoir during growing period, refilling reservoir after harvest and rehydrating growing media to field capacity; amount of water added to reservoir during growing period and to refill reservoir after harvest during WBT2

Treatment	Total water added (L)			Water added to reservoir (L)		
	mean		s.d.	mean		s.d.
cocopeat	61.8	ab[1]	2.82	58.0	ab	2.90
gravel	50.3	a	6.56	42.6	a	6.99
sand.cp	54.4	ab	8.36	50.8	ab	7.95
sand.pm	50.1	a	3.92	44.9	a	4.93
WaterUps®	70.5	b	6.88	66.2	b	6.82
significance	P= 0.0089			P= 0.00489		

(1)Mean separation within columns by Tukey (P<0.05)

Plant water use and water use efficiency were calculated using equations 6 and 7 respectively, and are shown in Table 23 for both harvest (wet) and dry lettuce weight. For this table, the water volume used was the total volume of water added to the reservoir during the experiment plus the water added after harvest to rehydrate the soil to its initial state

Table 23 - Water use (WU) and water use efficiency (WUE) of growing lettuce in WBT2. Calculated from total wet and dry weight of plants per bed and total water added to reservoirs during the experiment plus water used to rehydrate soil after harvest

Treatment	Wet weight				Dry weight			
	WU (L/kg)		WUE (g/L)		WU (L/kg)		WUE (g/L)	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
cocopeat	11.1 ab[1]	0.88	90.8 ab	6.95	257.7 a	21.71	3.9 ab	0.30
gravel	8.3 a	1.39	123.6 b	23.09	216.9 a	4.74	4.6 b	0.10
sand.cp	9.7 ab	1.08	104.3 ab	11.61	225.4 a	54.16	4.6 b	1.00
sand.pm	8.5 a	0.66	118.6 ab	8.98	202.4 a	17.36	5.0 b	0.46
WaterUps®	12.0 b	1.88	85.1 a	14.64	334.9 b	15.99	3.0 a	0.17
significance	P=0.0181		P=0.0302		P=0.0013		P=0.00634	

(1)Mean separation within column by Tukey (P<0.05)

4.6.3 Soil moisture

Soil moisture in each bed was measured in two ways. Soil water tension was measured by one electronic tensiometer buried 150mm deep in the centre of each bed. Moisture was also measured as a percentage of field capacity by a Pulse™ meter with measurements taken at 50, 100 and 200mm depth in each bed.

Measurements from Pulse™ meter

Figure 28 shows the mean of three soil moisture readings for each depth in all beds during WBT2. Water was added to all beds to fill reservoirs on day 36. The average soil water tension for each treatment is also shown for comparison, but there has been no calibration between soil moisture and soil water tension values.

There appeared to be a large variation in soil moisture measurements taken by the Pulse™ meter within the same bed, at the same depth on the same day. The meter manufacturer says that readings may vary and recommends taking three measurements from each container, which was done for this experiment.

As a check on whether this variation would effect experimental results, a series of 20 measurements at 100mm depth were taken on days 31 and 44 using an evenly spaced grid pattern across all beds. The day 31 measurements from each bed were compared with the three measurements taken on each of days 30 and 32 using the assumption that the moisture within a bed is unlikely to change much from one day to the next. There were no significant differences in any beds except bed 9 where the mean of one day was significantly different to one other day. Comparing the data from day 44 with days 43 and 45, produced a similar outcome; there were only significant differences within two beds (beds 12 and 16). From this it was concluded that three measurements were sufficient to produce a valid result.

The minimum soil moisture for each treatment at each depth is shown in Table 24.

Table 24 - Minimum soil moisture as a percentage of field capacity at any time during WBT2 measured by a Pulse™ meter at 50, 100 and 200mm depths

Treatment	Soil moisture (%) 50 mm depth			Soil moisture (%) 100 mm depth			Soil moisture (%) 200 mm depth		
	mean		s.d.	mean		s.d.	mean		s.d.
cocopeat	48.7	bc[1]	14.74	56.3	ab	11.58	67.8	b	8.29
gravel	40.8	b	10.57	50.9	ab	10.89	36.8	a	8.79
sand.cp	42.2	b	9.46	60.4	bc	9.15	54.9	ab	11.88
sand.pm	15.9	a	6.31	44.8	ab	13.58	74.2	b	25.91
WaterUps®	60.8	c	12.33	73	c	12.08	70.6	b	19.74
significance	P= 0.0000000436			P= 0.000109			P= 0.0000946		

[(1)]Mean separation within columns by Tukey (P<0.05)

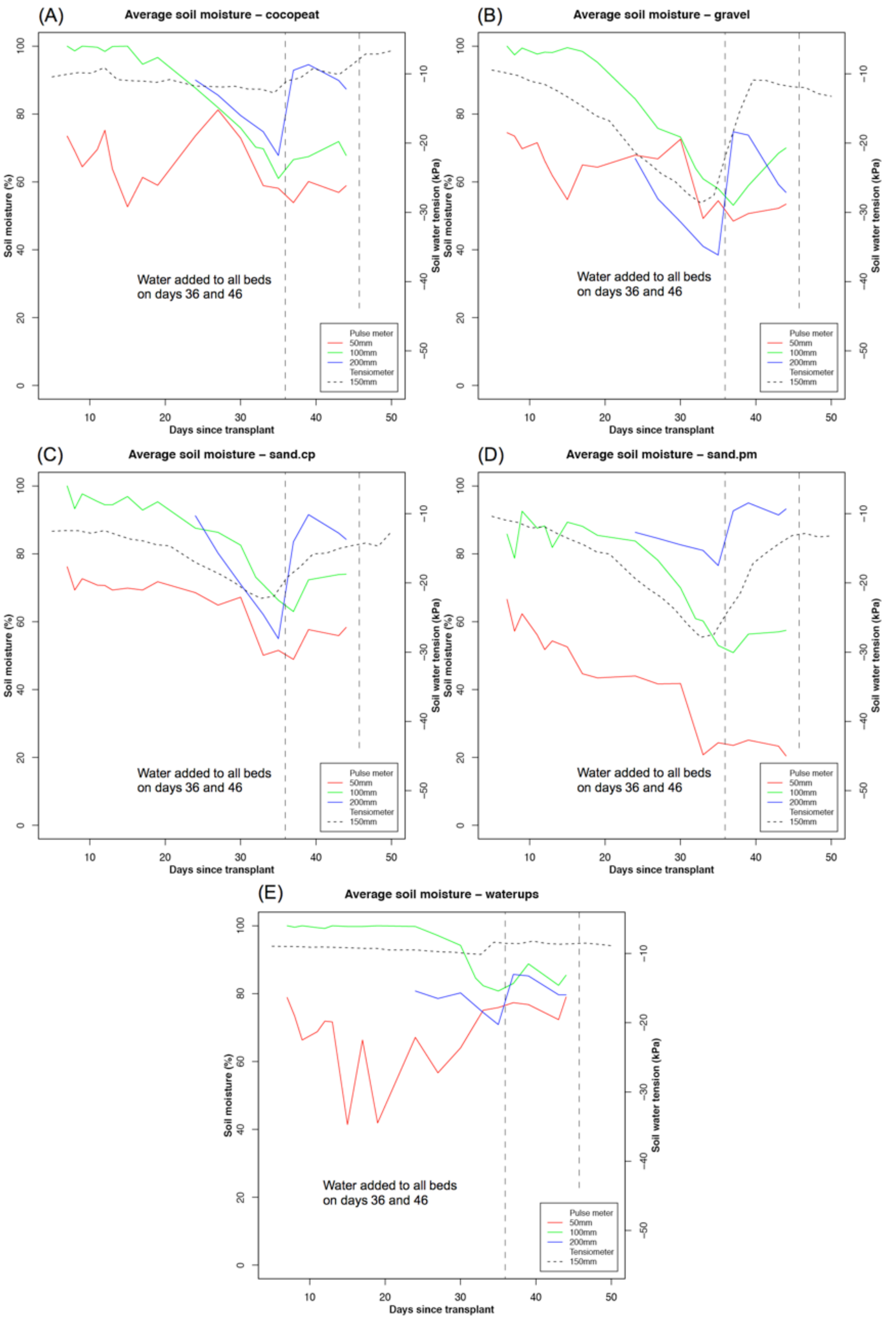

Figure 28 - Soil moisture as a percentage of field capacity in each bed in WBT2 at depths of 50, 100 and 200mm below the surface from a Pulse^{TM} meter and average soil water tension from a tensiometer 150mm below the surface for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps®. Results displayed are the mean of three measurements at each depth in each bed. Pulse^{TM} measurements were taken on day 6 then an average of every two days to day 44 except measurements at 200mm depth were not taken until day 24. Days when water was added to reservoirs indicated by vertical dashed lines. Soil moisture % and soil water tension scales have not been calibrated together.

Soil moisture measurements were taken on day 35 before refilling the reservoirs (Table 25) and day 44 before harvest (Table 26).

Table 25 - Soil moisture as a percentage of field capacity before refilling reservoirs in WBT2 measured with Pulse™ meter at 50, 100 and 200mm depths

Treatment	Soil moisture (%) 50mm depth mean		s.d.	Soil moisture (%) 100mm depth mean		s.d.	Soil moisture (%) 200mm depth mean		s.d.
cocopeat	58	b[1]	8.10	61	a	11.49	68	b	8.29
gravel	54	b	11.28	58	a	9.01	38	a	8.34
sand.cp	52	b	10.73	66	ab	9.84	55	ab	11.79
sand.pm	24	a	9.76	53	a	16.13	77	b	26.12
WaterUps®	76	c	3.55	81	b	13.33	71	b	19.49
significance	P=5.5e-13			P=0.00028			P=0.0000965		

(1)Mean separation within columns by Tukey (P<0.05)

Table 26 - Soil moisture as a percentage of field capacity measured with Pulse™ meter at 50, 100 and 200mm depths before harvesting lettuces in WBT2

Treatment	Soil moisture (%) 50mm depth mean		s.d.	Soil moisture (%) 100mm depth mean		s.d.	Soil moisture (%) 200mm depth mean		s.d.
cocopeat	59	b[1]	13.94	68	ab	14.98	87	b	7.87
gravel	53	b	16.02	70	ab	14.69	57	a	15.37
sand.cp	58	b	13.23	74	ab	8.43	84	b	9.53
sand.pm	20	a	7.32	57	a	13.34	93	b	11.30
WaterUps®	79	c	15.84	85	b	15.53	80	b	15.09
significance	P=0.00000000141			P=0.00233			P=0.00000255		

(1)Mean separation within columns by Tukey (P<0.05)

Measurements from tensiometers

Measurements of soil water tension were made using electronic tensiometers placed at 150mm depth in the centre of each bed. Measurements from the tensiometers were recorded hourly. Graphs of the raw measurements from each bed are in Figure 29.

There was a lot of noise and apparent erroneous data in the raw tensiometer data. The following steps were done to provide clean data for analysis (Figure 30):

- There was a lot of variation in many beds in the days before day 20. This was possibly due to lack of good contact between the growing medium and the tensiometer until the growing medium settled. All data before day 20 was removed from the data set.
- The tensiometer in bed 16 (gravel) suffered from an air leak and gave consistent measurements near 0kPa so data for this bed was removed.

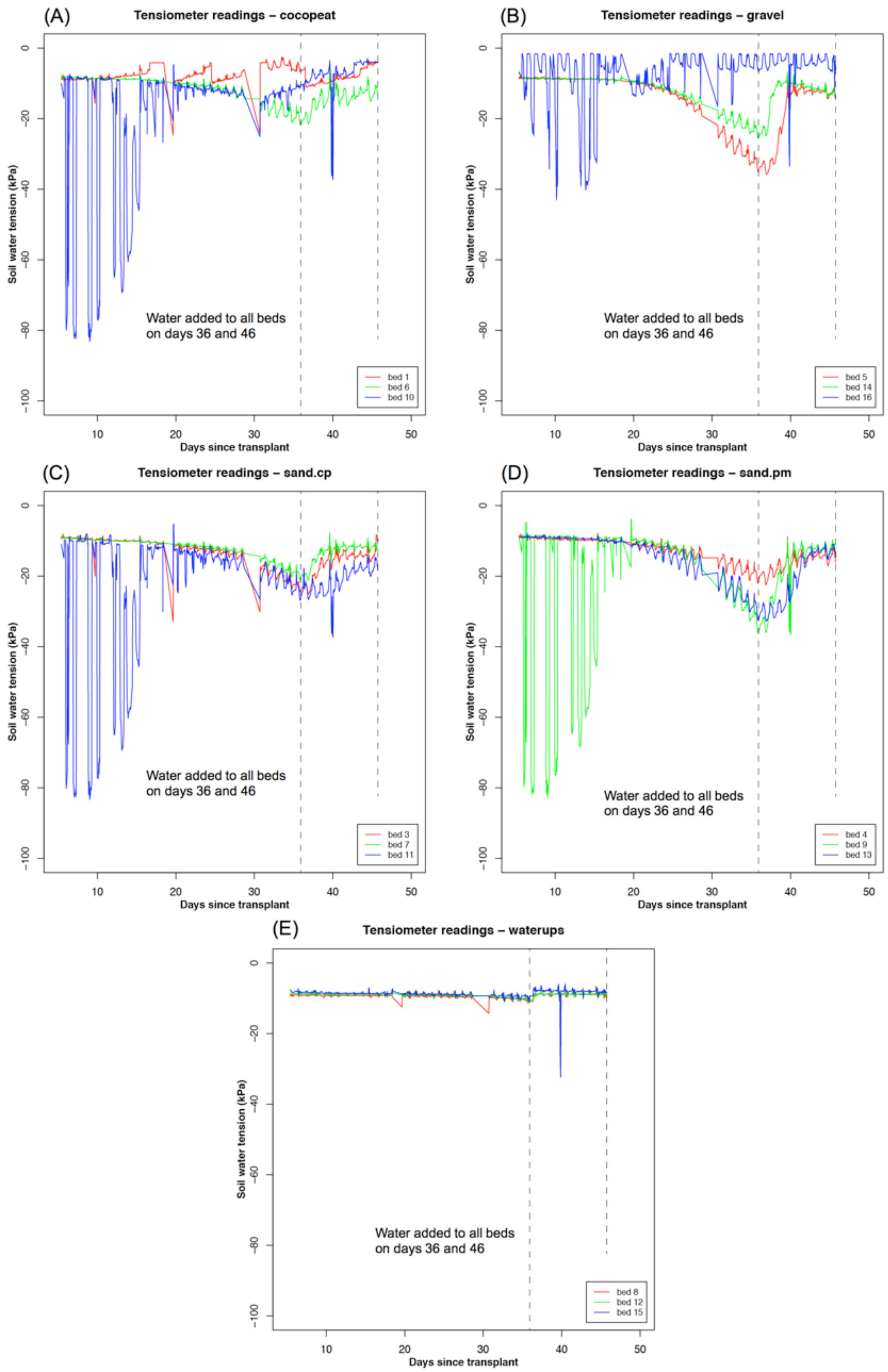

Figure 29 - Soil water tension for wicking beds in WBT2 for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps® from tensiometers placed 150mm below the surface of the growing medium. Hourly measurements were made using electronic tensiometers placed at 150mm depth in the centre of each bed. Days when water was added to reservoirs indicated by vertical dashed lines.

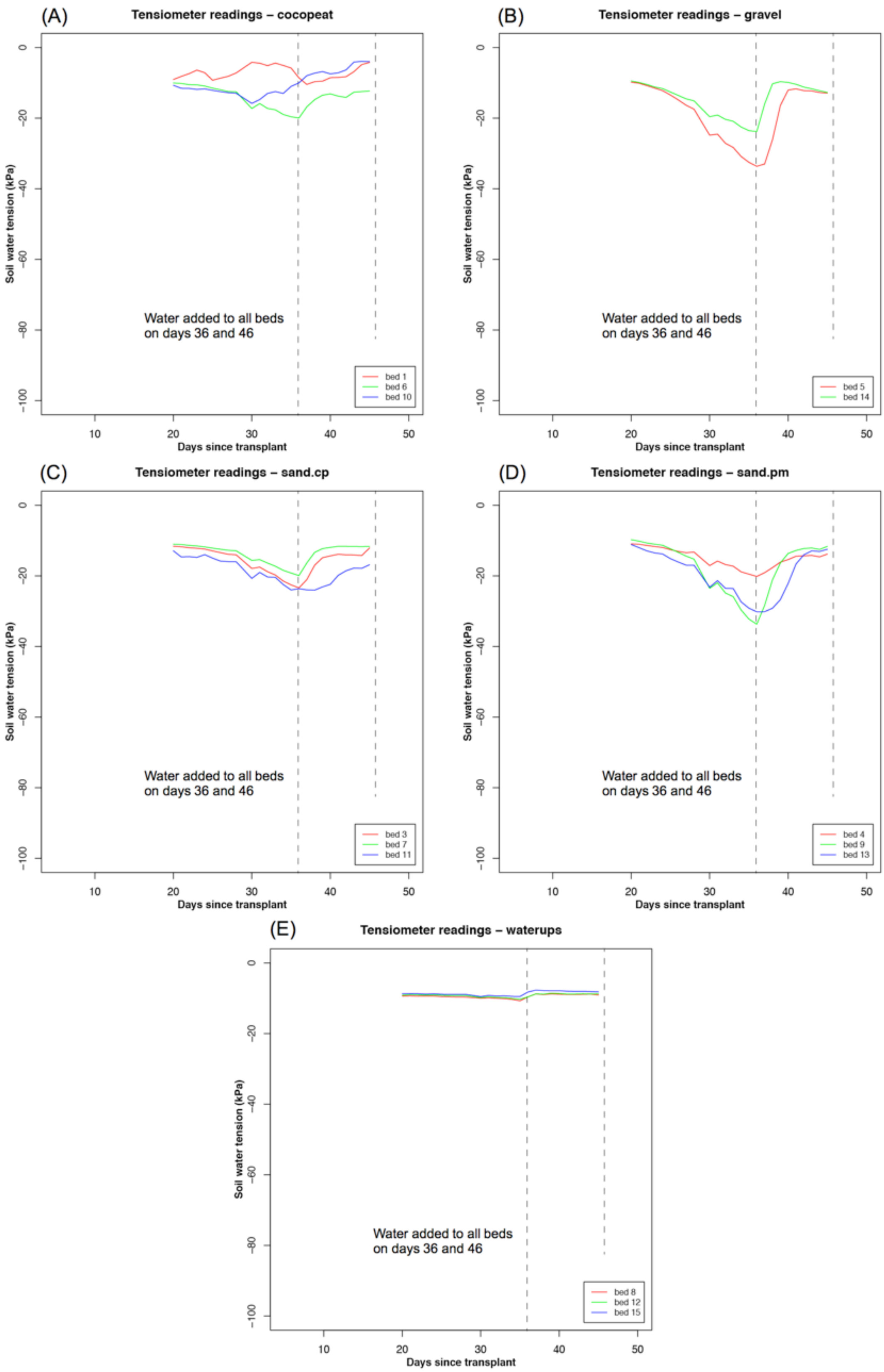

Figure 30 - Soil water tension (after removing anomalous data and calculating 24 hour rolling average) for all wicking beds in WBT2 for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps® from electronic tensiometers placed 150mm below the surface of the growing medium recording measurements hourly. Days when water was added to reservoirs indicated by vertical dashed lines.

- A few readings had sudden spikes in the measurements that are unlikely to be related to real soil moisture changes. Some of these are the first readings after a flat battery in the data loggers was replaced; the cause of others are unknown. When spikes were identified, the data recorded at that time was removed from the datasets for all beds. The data removed was at day 30.71 and the days between 39.82 and 40.03.

- There was a distinct cycle of daily variation in all tensiometer readings. A rolling 24 hour average was used to smooth out these variations.

The mean soil water tension for each treatment derived from the cleaned tensiometer data is shown in Figure 31.

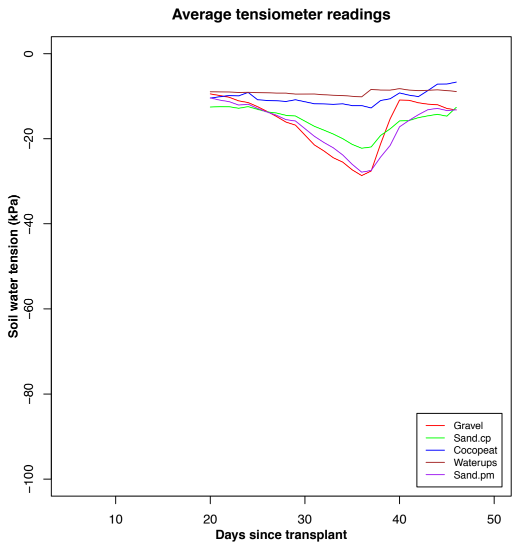

Figure 31 - Mean soil water tension for each treatment in wicking beds in WBT2. Data is from one tensiometer in centre of bed 150mm below soil surface with anomalous data points removed and a 24 hour rolling average calculated

The mean minimum soil water tension for each treatment derived from the cleaned tensiometer data is shown in Table 27.

Table 27 - Minimum and maximum soil water tension in wicking beds in WBT2 from one tensiometer in centre of bed 150mm below soil surface with anomalous data points removed and a 24 hour rolling average calculated

Treatment	Minimum soil water tension (kPa)			Maximum soil water tension (kPa)		
	mean		s.d.	mean		s.d.
cocopeat	-15.3	ab[1]	4.7	-3.7	b	1.69
gravel	-29.0	b	7.07	-7.2	ab	0.64
sand.cp	-22.6	ab	2.29	-9.1	a	2.08
sand.pm	-28.2	b	7.00	-9.5	a	0.76
WaterUps®	-10.3	a	0.72	-6.4	ab	0.42
significance	P=0.00486			P=0.0031		

(1)Mean separation within columns by Tukey (P<0.05)

The tensiometers were located 150mm below the soil surface and soil moisture readings were made with the Pulse™ meter at 50, 100 and 200mm depths. The mean of the 100 and 200mm depth readings has been compared with the tensiometer readings from the same day. There is a moderate correlation (r^2=0.4456) between the two different measuring techniques (Figure 32).

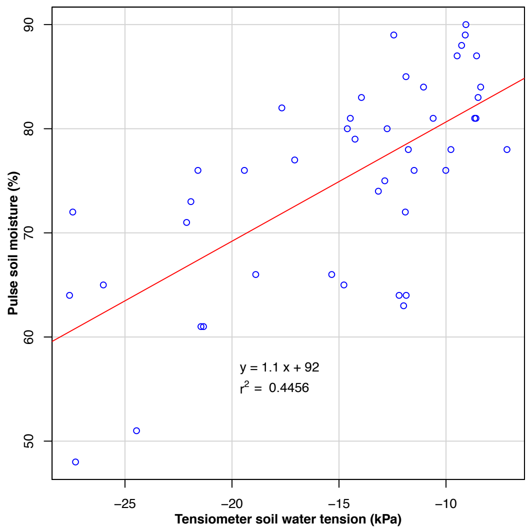

Figure 32 - Correlation between the average of pairs of soil moisture measurements in all beds in WBT2 made with a Pulse™ meter at 100mm and 200mm depths and soil water tension measurements from an electronic tensiometer in each bed at 150mm depth.

4.6.4 Reservoir water levels

The drop in the level of free water in the reservoir was measured on the indicator tube on the side of each wicking bed. Figure 33 shows the change in water level over time for each bed. The lowest water level reached during the experiment is shown in Table 28. As the reservoirs are 200mm deep, a drop of 200mm indicates that there is no free water in the reservoir. As in WBT1, there still would have been available water in the sand and cocopeat reservoirs when the indicator tube showed empty.

Table 28 - Mean maximum drop in level of free water from full level in 200mm deep reservoir layer of wicking beds in WBT2

Treatment	Water level drop (mm) mean	s.d.
cocopeat	200	0
gravel	92	1.53
sand.cp	200	0
sand.pm	200	0
WaterUps®	166	42.76

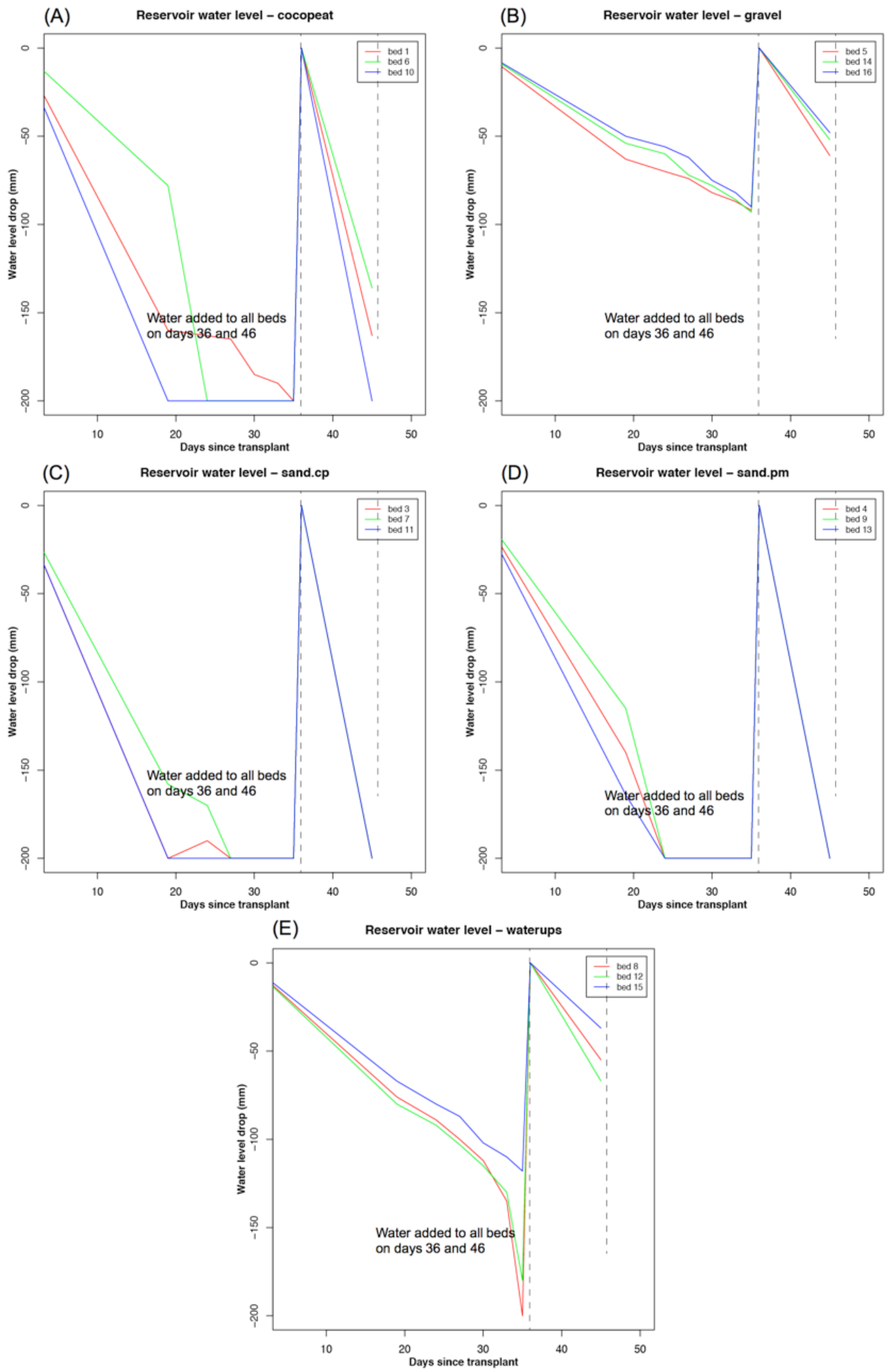

Figure 33 - Level of water over course of the experiment in indicator tube of 200mm deep reservoir of each bed in WBT2 for reservoir treatments (A) cocopeat, (B) gravel, (C) sand.cp, (D) sand.pm, (E) WaterUps®, where 0=reservoir full and -200=no free water in reservoir. Measurements made on day 19 then an average of every 3 days until day 36 then on day 45.

4.6.5 Plant canopy area

Figure 34 shows the mean plant area as a percentage of total bed area for each treatment up to 24 days after planting. All treatments showed a steady rate of growth. There were no significant differences in plant area between treatments.

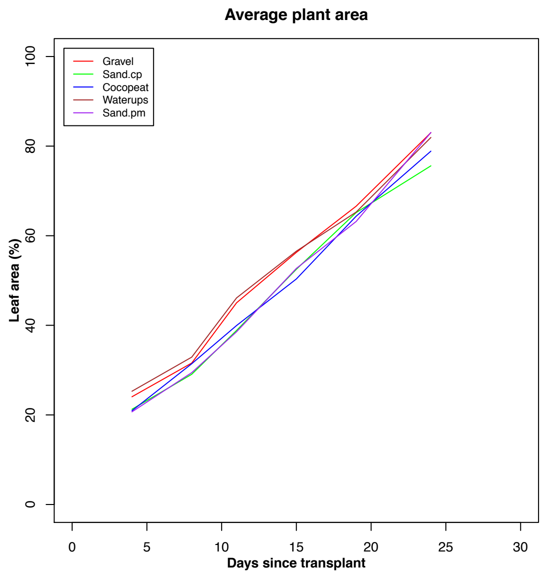

Figure 34 - Mean percentage of bed surface area covered by leaves by treatment in WBT2. Measured using Canopeo app on days 4, 8, 11, 15, 19 and 24 after transplant

Figure 35 contains photos of all beds immediately before the lettuces were harvested. Some tip burn on the lettuces is evident in all treatments.

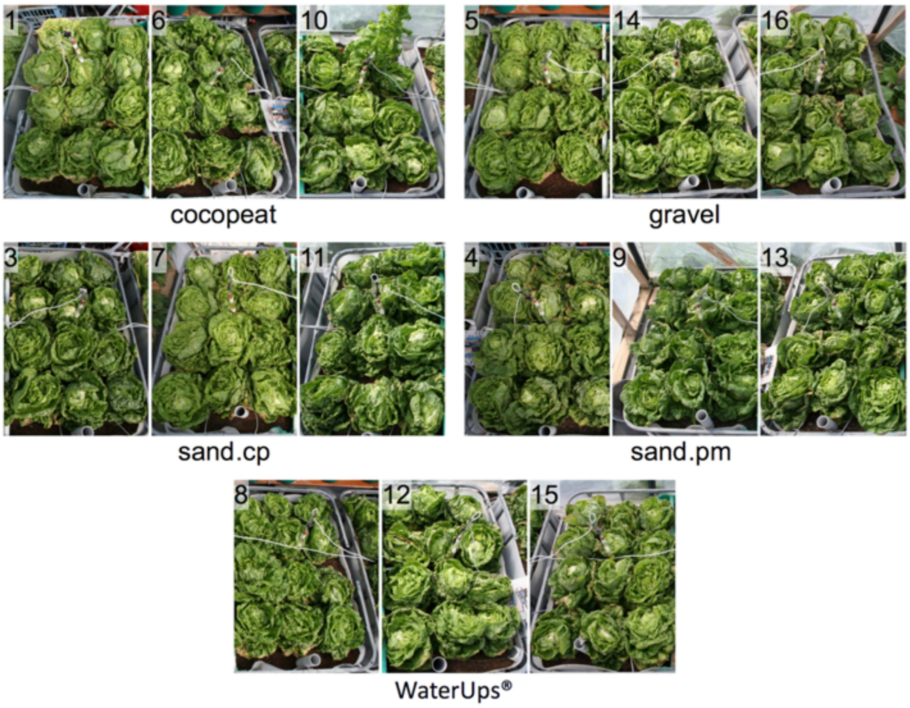

Figure 35 - Lettuce in WBT2 on the day of harvest, 45 days after transplant. Treatments: beds 1,6,10 - cocopeat; beds 5,14,16 - gravel; beds 3,7,11 - sand.cp; beds 4,9,13 - sand.pm, beds 8,12,15 WaterUps®

4.6.6 Plant root growth

After conclusion of WBT2, the sand.pm beds were deconstructed and roots were found to have grown through the geotextile and into the sand reservoir layer. Figure 36 is a photograph of roots on the underside of the geotextile.

Figure 36 - Photograph of the underside of geotextile removed from sand.cp treatment after WBT2 showing roots that have grown through the geotextile and into the sand filled reservoir

4.6.7 Soil electrical conductivity

Soil electrical conductivity (EC) was lower at the end of WBT2 than at the start at both 50 and 100mm depths except for the WaterUps® treatment at 50mm depth where EC increased by 0.28dSm^{-1} (Figure 37, Table 29). The potting mix in the sand.pm treatment had significantly lower EC at both 50mm (P= 0.0000376) and 100m (P= 0.0000268) depths than the cocopeat mix treatments.

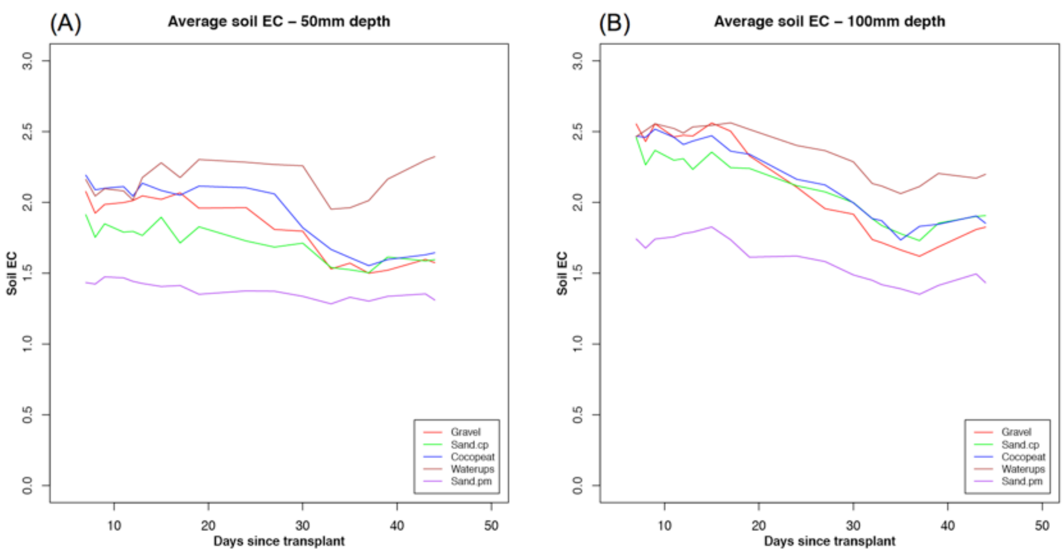

Figure 37 - Electrical conductivity (dSm^{-1}) of growing medium at (A) 50mm and (B) 100mm below surface in WBT2. Measurements were taken using a Pulse^{TM} meter on day 6 then an average of every two days to day 44

Table 29 - Difference between electrical conductivity (EC) within beds at the start and end of WBT2 at 50mm and 100mm below the soil surface

Treatment	EC difference (end-start) (dSm^{-1})					
	50mm depth			100mm depth		
	mean		s.d.	mean		s.d.
cocopeat	-0.46	a[1]	0.17	-0.59	a	0.25
gravel	-0.36	ab	0.20	-0.63	a	0.18
sand.cp	-0.16	b	0.20	-0.37	ab	0.18
sand.pm	-0.12	b	0.07	-0.11	b	0.39
WaterUps®	0.28	c	0.28	-0.31	ab	0.37
significance	P=0. 875e$^{10-8}$			P=0.00191		

(1)Mean separation within columns by Tukey ($P<0.05$)

4.6.8 Temperature and humidity

Air temperature in the polytunnel during WBT2 and WBT3 ranged from a minimum of 7.2°C to a maximum of 44.8°C. The mean daily minimum was 13.3°C and the mean daily maximum was 31.6°C (Figure 38). Humidity also varied on a daily cycle from a minimum of 10% to a maximum of 95%.

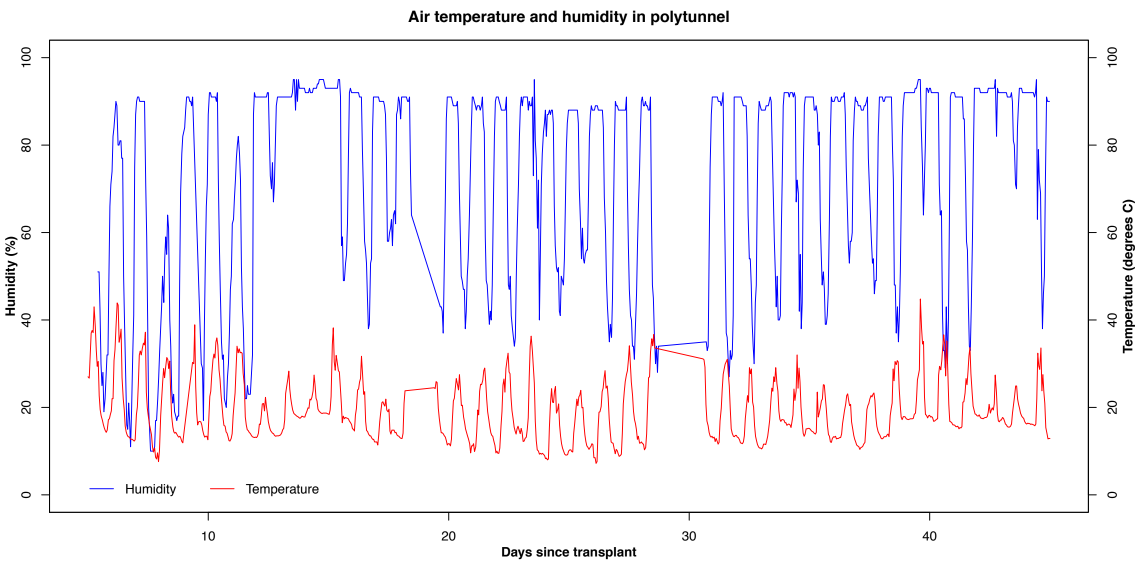

Figure 38 - Hourly temperature and humidity in the polytunnel during WBT2. Measurements were made hourly except for interruptions on days 18-19 and 28-30

Soil temperatures at 100mm depth fluctuated between 14.7°C and 26.2°C. Figure 39 shows the variation in soil temperatures at this depth throughout WBT2. Soil temperatures were not taken at the same time each day. Figure 39 also shows the air temperatures at the time that the soil temperature readings were taken.

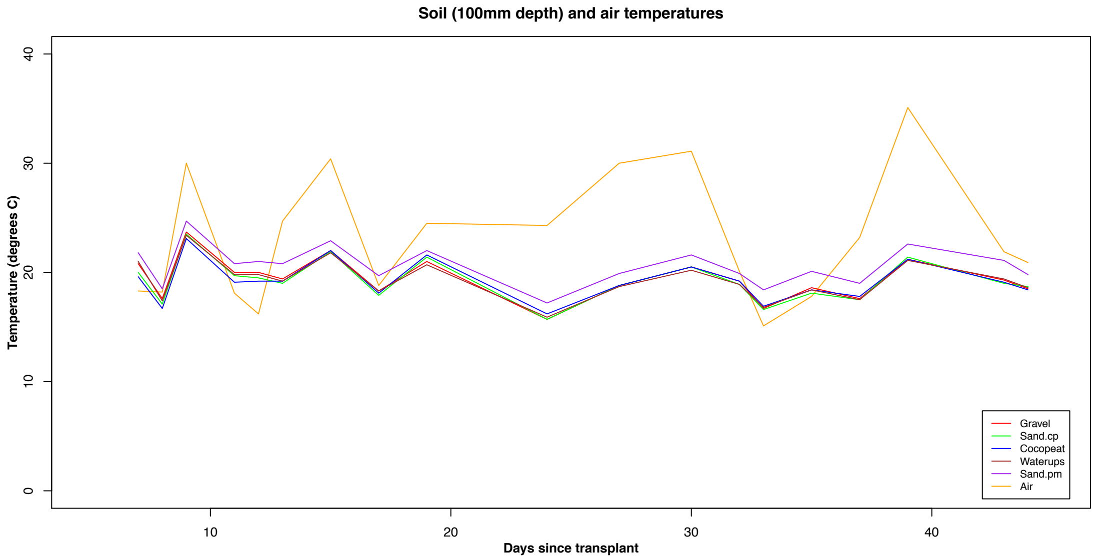

Figure 39 - Mean soil temperature per bed during WBT2 at 100mm below soil surface from a Pulse™ meter on day 6 then an average of every two days to day 44 and air temperature within the polytunnel housing the beds at the time soil temperature measurements were made

Across all treatments, mean soil temperature was cooler at 200mm than at 50 or 100mm (Table 30). Soil was warmer at all depths in the potting mix in the sand.pm treatment than the cocopeat mix in other treatments (Table 31). There was no interaction between treatment and depth affecting soil temperatures.

Table 30 - Mean soil temperature across all treatments at all depths throughout WBT2. Measurements made with a Pulse™ meter

Depth	Soil temperature (°C)		
	mean		s.d.
50 mm	19.7	b[1]	2.86
100 mm	19.6	b	2.00
200 mm	18.7	a	1.46
significance	$P=6.04e^{-12}$		

(1)Mean separation within column by Tukey (P<0.05)

The sand.pm treatment was warmer than all other treatments at all depths. Apart from this, there were no significant differences in soil temperature between treatments at any depth (Table 31).

Table 31 - Mean soil temperature for each treatment at 50, 100 and 200mm depth throughout WBT2. Measurements made with a Pulse™ meter

Treatment	Soil temperature (°C)								
	50mm depth			100mm depth			200mm depth		
	mean		s.d.	mean		s.d.	mean		s.d.
cocopeat	19.4	a[1]	2.88	19.3	a	1.88	18.6	a	1.14
gravel	19.6	a	2.76	19.4	a	1.94	18.4	a	1.29
sand.cp	19.4	a	2.91	19.2	a	1.98	18.2	a	1.39
sand.pm	20.5	b	2.87	20.6	b	1.95	19.8	b	1.49
WaterUps®	19.4	a	2.74	19.3	a	1.90	18.4	a	1.36
significance	P=0.00119			P=3.26e-13			P=1.44e-14		

(1)Mean separation within columns by Tukey (P<0.05)

4.7 Wicking bed trial 3 (WBT3) - lettuce in small wicking beds

WBT3 was conducted using small wicking beds growing one lettuce per bed. It was designed to test the effect of the presence or absence of a geotextile layer between the reservoir and growing layers. Three replicates of each treatment were used.

4.7.1 Plant weight

Plants were weighed after harvest to give a wet weight (Table 32). There were no significant differences in plant weight between treatments.

Table 32 - Mean wet weight of lettuce stems and leaves after harvest from WBT3

Treatment	Plant weight (g)		
	mean		s.d.
cp.gtex	586	a[1]	79
cp.none	661	a	108
sand.none	597	a	35
significance	not significant		

(1)Mean separation within columns by Tukey (P<0.05)

4.7.2 Water use

Table 33 shows the total amount of water added to beds during WBT3 including refilling the reservoirs and re-saturating the soil after harvest, and the total water added to the reservoirs before rehydrating the soil (as per WBT1). The sand.none treatment required significantly less water than the other treatments. The geotextile layer made no difference to the amount of water added to the cocopeat treatments.

Table 33 - Total water added per bed including additions to reservoir during growing period, refilling reservoir after harvest and rehydrating growing media to field capacity; amount of water added to reservoir during growing period and to refill reservoir after harvest during WBT3

Treatment	Total water added (L)			Water added to reservoir (L)		
	mean		s.d.	mean		s.d.
cp.gtex	6.93	b[1]	0.97	5.99	b	0.88
cp.none	6.99	b	0.47	5.96	b	0.43
sand.none	4.91	a	0.40	4.04	a	0.35
significance	P=0.0135			P=0.0112		

(1)Mean separation within columns by Tukey (P<0.05)

4.7.3 Soil moisture

The soil moisture measured by the Pulse™ meter at 50, 100 and 200mm depths is shown in Figure 40. The reservoirs were refilled on day 34 and resulted in an increased soil moisture at 200mm depth in all treatments. However, the sand.cp treatment did not recover to the same level as the other treatments. There was a smaller rise in soil moisture after the reservoir refilling at shallower depths in all treatments.

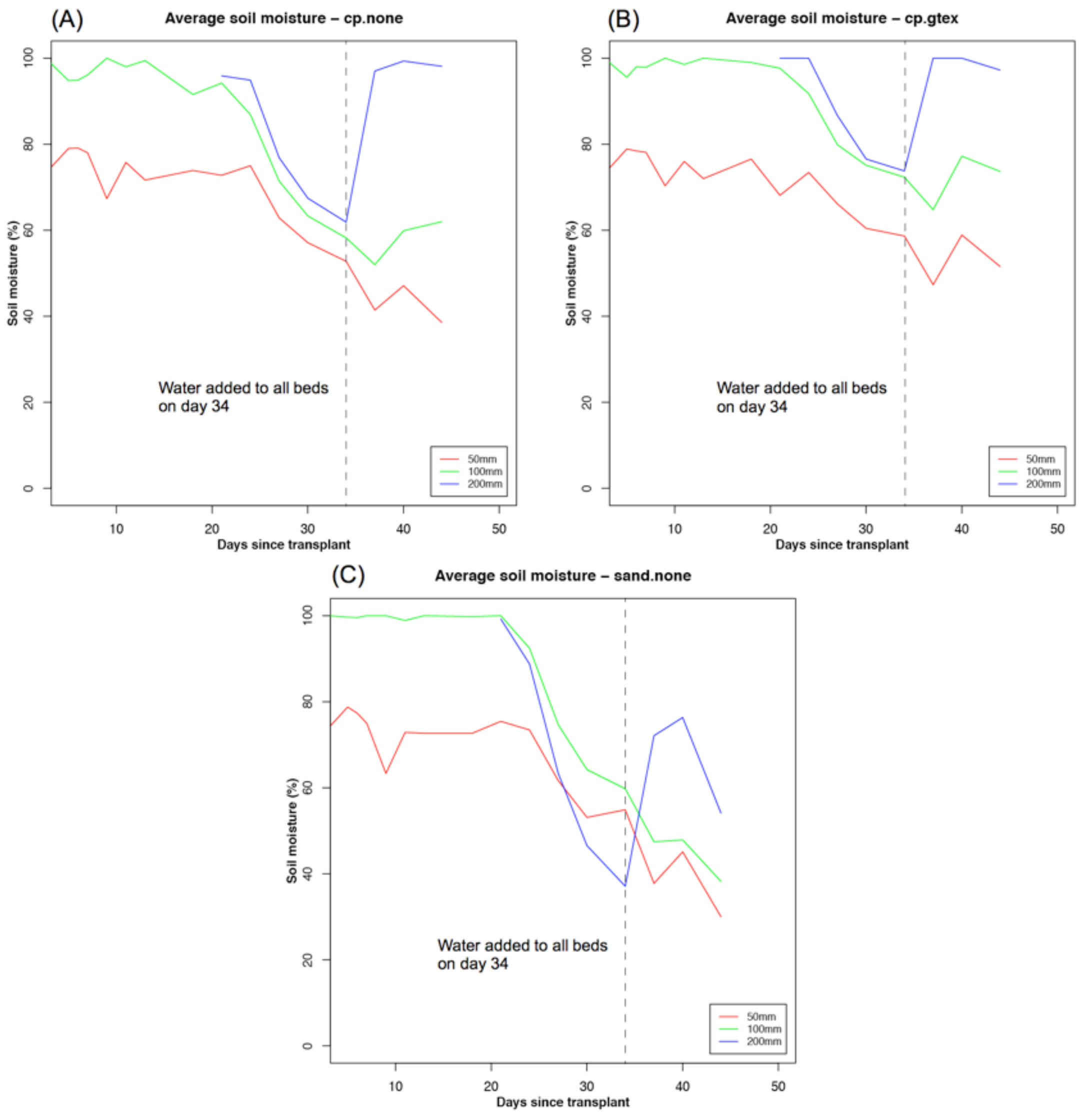

Figure 40 - Soil moisture as a percentage of field capacity in each bed in WBT3 at depths of 50, 100 and 200mm below the surface for reservoir treatments (A) cp.gtex, (B) cp.none, (C) sand.none from a Pulse^{TM} meter. Results displayed are the mean of three measurements at each depth in each bed. Measurements were taken on day 2 then an average of every 2.5 days to day 44 except measurements at 200mm depth were not taken until day 21. Days when water was added to reservoirs indicated by vertical dashed lines.

Just before the reservoirs were refilled on day 34, there was no significant differences between treatments in soil moisture at 50 and 100mm depths. The sand.none treatment was significantly drier than the other treatments at 200mm depth (Figure 40, Table 34).

Table 34 - Mean soil moisture as a percentage of field capacity measured by Pulse^{TM} meter in WBT3 at 50, 100 and 200mm depth on day 34 before refilling reservoirs

Treatment	Soil moisture (%)								
	50mm depth			100mm depth			200mm depth		
	mean		s.d.	mean		s.d.	mean		s.d.
cp.gtex	59	a[1]	15.43	72	a	14.05	74	b	15.62
cp.none	53	a	9.46	58	a	13.28	62	b	13.91
sand.none	55	a	10.75	60	a	12.67	37	a	7.20
significance									

(1)Mean separation within columns by Tukey (P<0.05)

4.7.4 Soil electrical conductivity

Soil electrical conductivity as measured by a Pulse^{TM} meter was lower at the end of the experiment than at the start in all treatments at both 50mm and 100mm depth. The cp.gtex treatment had a significantly smaller difference than the other treatments at 50mm depth and the sand.none treatment had a significantly greater difference at 100mm depth (Figure 41, Table 35).

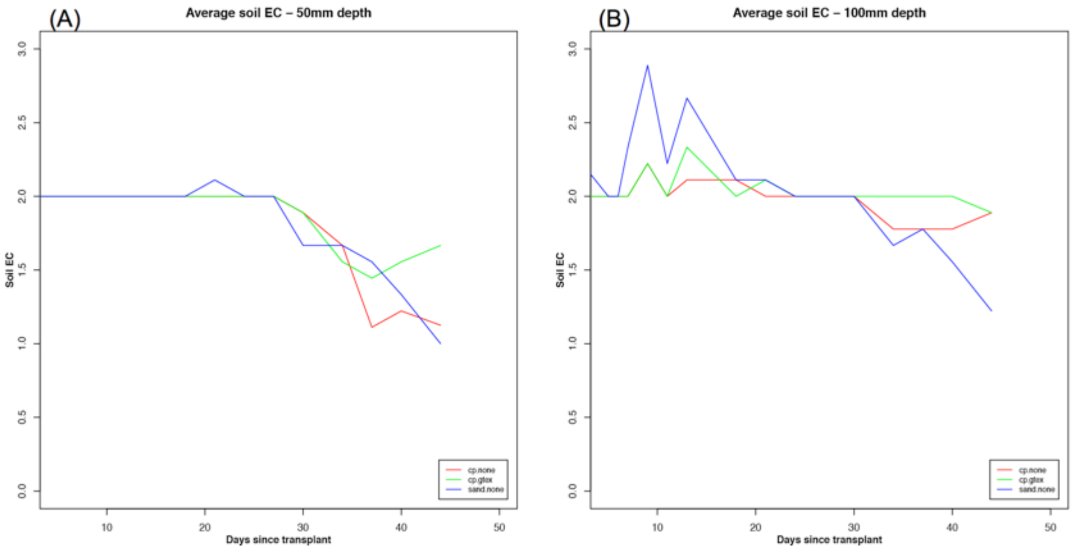

Figure 41 - Soil electrical conductivity EC (dSm^{-1}) in WBT3 at (A) 50mm depth and (B) 100mm depth

Table 35 - Difference between electrical conductivity (EC) within beds at the start and end of WBT3 at 50mm and 100mm below the soil surface

Treatment	EC difference (end-start)					
	50mm depth			100mm depth		
	mean		s.d.	mean		s.d.
cp.gtex	-0.27	b[1]	0.16	-0.33	b	0.21
cp.none	-0.48	a	0.17	-0.51	b	0.16
sand.none	-0.50	a	0.11	-0.88	a	0.09
significance	P=0.00413			P=0.000000851		

(1)Mean separation within columns by Tukey (P<0.05)

4.7.5 Soil temperature

Soil temperatures measured by the Pulse™ meter in the WBT3 beds fluctuated between 13.9°C and 40.6°C. Figure 42 shows the variation in mean soil temperatures at 100mm depth throughout WBT3. There were no significant differences in mean soil temperatures between depths or treatments in WBT3 (Table 36).

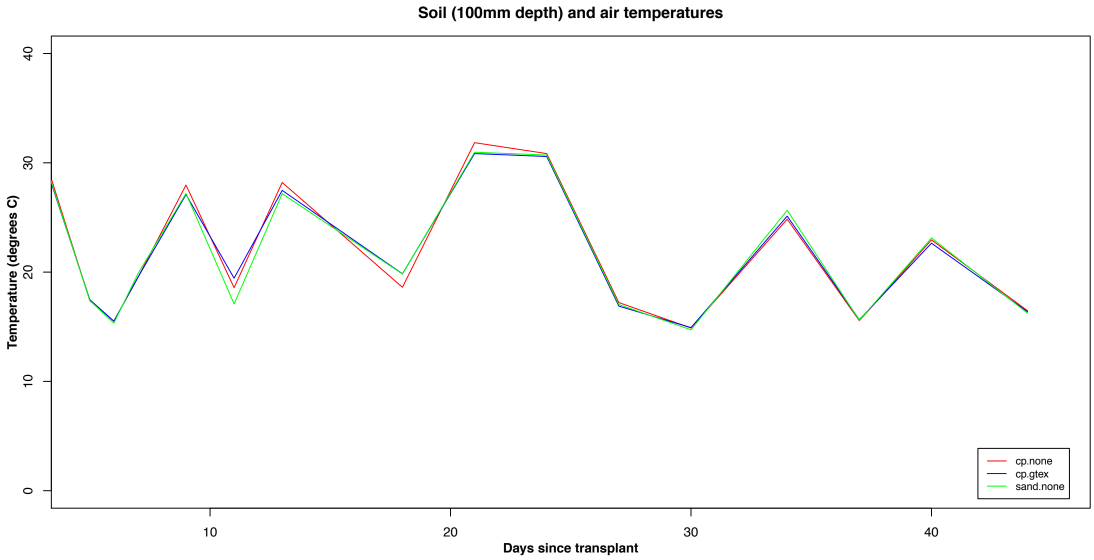

Figure 42 - Mean soil temperature by treatment during WBT3 measured by a Pulse™ meter 100mm below soil surface. Measurements were taken on day 2 then an average of every 2.5 days to day 44

Table 36 - Mean soil temperature by treatment at 50, 100 and 200mm below soil surface throughout WBT3. Measurements by Pulse™ meter

	Mean soil temperature (°C)					
	cp.gtex		cp.none		sand.none	
	mean	s.d.	mean	s.d.	mean	s.d.
50 mm depth	21.9	5.90	21.8	6.03	21.9	6.01
100 mm depth	21.4	5.98	21.6	6.28	21.4	6.10
200 mm depth	21.3	6.59	21.6	6.85	21.7	6.98

4.8 Comparison between WBT1 and WBT2

For some of the measurements made, data presented earlier as separate results for WBT1 and WBT2 have been combined into a single graph for ease of comparison.

The average rates of water level fall in the reservoirs of the gravel and WaterUps® treatments in WBT1 and WBT2 have been derived from the data used for Figure 25 and Figure 33. The rates of fall are shown in Figure 43.

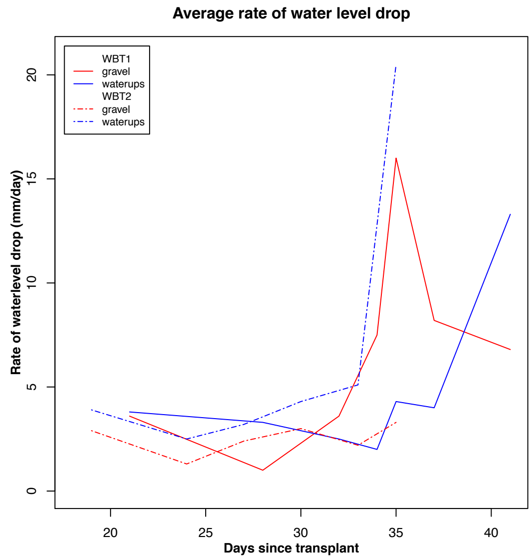

Figure 43 - Daily rate of reservoir water level drop in indicator tubes for gravel and WaterUps® treatments in WBT1 and WBT2 from start of experiment to time of first reservoir refill

Figure 44 shows the mean soil water tension 150mm below the soil surface during WBT1 and WBT2. These are duplicates of Figure 24 and Figure 31, presented together for more convenient comparison.

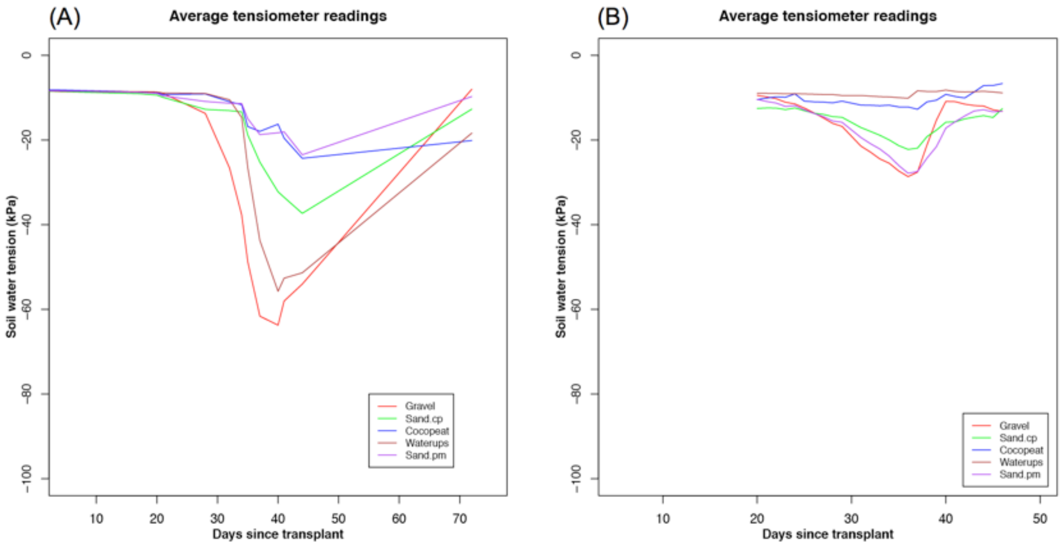

Figure 44 - Mean soil water tension for each treatment in (A) WBT1 and (B) WBT2 from tensiometers buried 150mm below soil surface

Table 37 shows number of days before soil water tension dropped below -20kPa when soil can be considered dry for container growing.

Table 37 - Mean number of days after transplant for each treatment before soil water tension dropped below -20kPa

Treatment	Days after transplant WBT1	WBT2
cocopeat	-[1]	-
gravel	32	31
sand.cp	37	35
sand.pm	44	32
WaterUps®[2]	35	-

(1)one cocopeat bed did drop below -20kPa on day 44 but has been excluded from these results because it did not rehydrate after the reservoir was refilled

(2)The WaterUps® treatment used medium grade perlite as the wicking medium in WBT1 and sand in WBT2

5 DISCUSSION

The function of the reservoir in a wicking bed is to store water and deliver the water to the growing medium above. One of the main benefits of growing plants in wicking beds is the reduced workload due to less frequent watering compared with other growing systems. Watering frequency is affected by the water holding capacity of the reservoir which is a function of the pore space in the reservoir medium. For a given volume, a material with a large pore space will hold more water than one with a small pore space and the reservoir will require less frequent refills.

Transfer of water from the reservoir to the growing medium is done by capillary rise through the reservoir medium. The reservoir medium should have sufficient wicking ability to meet two aims. Firstly, it should be able to deliver water at a sufficient rate and quantity to match evapotranspiration from the plants in the growing medium. Secondly, it should be able to wick water from the full depth of the reservoir. As the water level in reservoir drops, the wicking height increases; if the reservoir is deeper than the maximum wicking height of the material used in the reservoir, not all of the water in the reservoir will be available to the plants and the time between refills will be shorter than would be indicated by the total water capacity of the reservoir.

Most of the recommendations in the popular literature for reservoir media for wicking beds are for inorganic materials such as sand, gravel or scoria. Gravel was used in wicking bed experiments by Sullivan et al. (2015) and Semananda et al. (2016). Austin (2011) suggests using a soil-based growing medium to fill both the growing and reservoir layers with no division between the two layers. The cocopeat mix treatment was included in the current study based on this recommendation. Although not included in the current study, it has been the experience of this author that using a purely organic substrate in the reservoir layer can result in problems as the organic material decomposes under anerobic conditions and loses its structure. For this reason, the cocopeat mix which is 90% organics may not be a suitable long-term reservoir medium and a mix with a greater proportion of inorganic materials may be more suitable. Nevertheless, the cocopeat mix was an adequate medium for use in the short term of this study.

While the main aim of this study was to investigate the suitability of various potential reservoir materials for use in wicking beds, it is important to recognise that the growing medium will also have a significant effect on the growth of plants in the system. The growing medium must have sufficient wicking ability to transfer water supplied from the reservoir to the plant roots as well as providing support and nutrients for the plants.

5.1 Media wicking ability and effect on choice of reservoir medium

The reservoir in a typical wicking bed is 200mm deep so, for all the water in the reservoir to be available to plant roots in the growing medium, water needs to move by capillary action 200mm through the reservoir material. If water cannot move this distance then not all of the water in the reservoir will be available to the plants. Of the reservoir materials tested for capillary rise, a rise of 200mm or greater was measured for crusher dust, washed sand, river sand, and cocopeat mix. Scoria, river gravel, crushed gravel and woodchips all had a capillary rise of less than 200mm, suggesting that that they would not be suitable choices for use in a 200mm deep reservoir.

The capillary rise results suggest that crushed gravel would only be suitable for reservoirs up to 100mm deep. In the wicking bed experiments, the water level in the gravel reservoirs dropped a maximum of 133mm and 92mm which left 34-54% of the total water still in the reservoir. However, as the water level in the reservoirs dropped, the soil moisture levels became drier in the gravel beds than the other treatments with the cocopeat growing medium. This suggests that transfer of water from the reservoir to the growing medium had stopped or substantially slowed because of the limited capillary rise in the gravel. This is supported by Semananda et al. (2016) who found no difference in the number of watering events required for gravel-filled reservoirs 150 and 300mm deep and no difference in the crop yield or water use efficiencies between the two depths.

River gravel and scoria both had very small capillary rise capabilities (17 and 35mm) indicating that they would only be suitable for shallow reservoirs. Scoria is often recommended for use in wicking bed reservoirs in the popular literature (e.g. Gardening Australia, October 2019, p50) because its porosity allows it to hold more water. However scoria does not hold more water than 10mm crushed gravel and has a lower capillary rise. It appears that scoria would be a poor choice for a wicking bed reservoir.

Although the capillary rise test for river sand was terminated earlier than other materials, there was a significant difference in the rise in washed and river sand at the time the test was ended. This suggests that different sands have varying performances in wicking bed reservoirs, although both sands tested were able to convey water to over 200mm height.

Perlite is known to have good capillary rise properties (Szmidt, Hitchon, & Hall, 1988; Wilson, 1980) despite having a coarse texture. However, there was a significant difference in capillary rise in the two grades of perlite tested. After 10 days, capillary rise in the fine grade perlite was 232mm but the medium grade perlite only reached 188mm. In WBT1 when the legs of the WaterUps® were filled with medium grade perlite, the water level in the reservoir dropped less and the soil moisture was less than in the beds in WBT2 when the perlite was replaced by sand. These results show that medium grade perlite is less suitable for wicking bed reservoirs than other media.

As well as the height to which water will rise, the volume of water that can be delivered to the growing media is important. The volume of water rising by capillary action was not measured, but the rate of rise can give an indication of the water volume available; the faster the rise, the greater the volume delivered to a specified height. In all media, the rate of capillary rise was greatest at the start and slowed as the level of rise grew. Crusher dust and the two sands had the shortest time to reach both 100 and 200mm.

A capillary rise rate of 5mm per day has been used as an indicator of the suitability of a substrate to supply water to growing plants (Schindler et al., 2017). Of the materials tested, only crusher dust, perlite (fine) and the sands were able to provide this rate of rise at 200mm. Water in the cocopeat mix rose at over 5mm per day up to 199mm but this was not significantly different to perlite(fine) or river sand (252 and 239mm). This criteria confirms the suitability of cocopeat mix, crusher dust, perlite(fine) and sand for use in wicking bed reservoirs up to 200mm deep, reaffirms that gravel is only suitable to 100mm deep, and shows the unsuitability of river gravel and scoria.

The rate of fall in the reservoir water levels in the gravel and WaterUps® treatments for both WBT1 and WBT2 from the start of the experiment to when water was added to the reservoirs has been calculated. Since the only mechanism for a fall in the water level in the reservoir is movement of the water into the growing layer the rate of fall in the reservoir level can be equated to the rate of movement of water into the growing layer. This was possible for only the gravel and WaterUps® treatments because they were the only reservoir treatments that contained sufficient free water for meaningful measurements from the indicator tubes.

In WBT1, the supply of water to the growing layer in the gravel beds as indicated by the rate of fall in the reservoir was a maximum seven days before refilling. We have seen earlier that the soil moisture levels were lowest at the time of refilling so it would appear that the gravel reservoir was unable to meet the water demands of the plants even though it still contained over half its water. At day 35 (seven days before the reservoirs were refilled), the water level in the gravel reservoirs were 95mm below the top and it has been shown in the capillary rise experiment that the rate of rise in gravel reduced markedly at about this level. In WBT2 the rate of fall in the gravel reservoir was still increasing when the reservoir was refilled on day 36. However this was done when the reservoir level was down 92mm so we cannot say that the pattern is different to WBT1.

In both WaterUps® trials, the rate of drop continued to increase until the reservoirs were refilled. The rate was much higher in WBT2 with sand compared to perlite in the legs of the WaterUps® modules. This indicates that the sand was transferring more water to the growing layer than the perlite and is further supported by the comparison of soil water tension in WBT1 and WBT2.

It is possible that some mechanism other than capillary rise allows water to move from the reservoir to the growing medium, particularly when the distance between the top of the free water and the bottom of the growing medium is greater than the maximum capillary rise potential of the reservoir medium Popular literature suggests that water vapour may transfer sufficient moisture to the growing medium and Wladitchensky (1966) describes the role that water vapour plays in capillary rise in fine pores, but it seems unlikely that this mechanism could supply sufficient water and no scientific publication has been found to support this suggestion. Another possibility is that plant roots may grow down into the reservoir layer and access water below the air gap. While a geotextile layer would inhibit this, some roots were found to penetrate the geotextile (Figure 36), confirming results of Semananda et al. (2020). In hydroponic systems, plants can grow successfully with roots crossing an air gap between the growing medium and a nutrient solution (Kratky, 1993) as would happen if roots grew into a gravel reservoir layer. However, in a wicking bed where the reservoir contains plain water rather than nutrient solution, plants are unlikely to thrive if the soil has insufficient moisture to facilitate nutrient transfer into the roots, even if their roots have entered the reservoir.

5.2 Water holding capacity

As noted above, the increased time between watering events is one of the main benefits of wicking beds compared to other growing systems. Provided that the reservoir can transfer sufficient water for the plant's needs and assuming that the reservoir has the same plan area as the growing medium, the factors affecting the time between watering events are the depth of the reservoir container and the pore space within the reservoir medium.

Pore space in the materials tested ranged from 34% in crusher dust to 71% in cocopeat mix. The inorganic medium with the greatest pore space was crushed gravel (49%) while the sands had a pore space of 39-40%. On this criteria alone it would appear that, of the inorganic materials, gravel would be the best choice to provide the largest water supply. However, as has been shown above, the wicking ability of gravel is limited and not all water from a gravel reservoir deeper than about 100mm would be accessible to the plants.

The maximum reservoir capacity for each material is a reservoir that is as deep as the maximum height to which the medium can sustain a capillary rise of 5mm per day (Table 11). Cocopeat, crusher dust and washed sand provide the largest capacity of approximately 150 litres.m^{-2} of bed area. Based on an evapotranspiration rate of 5mm per day, these reservoirs would only require filling approximately once each month. They would, however, differ greatly in their depths: 470mm for crusher dust, 368mm for sand and 199mm for cocopeat mix. The greater depth for sand and crusher dust would add to the cost of constructing the wicking beds. This would need to be considered against reduced operating costs of less frequent watering. As a point of comparison, hydroponic systems produce the greatest yield with as many as 5-7 watering events per day (Pires et al., 2011; Suazo-López et al., 2014).

Based on the actual capacity of the wicking bed reservoirs used in WBT1 and WBT2, the expectation was that WaterUps® would provide greatest period between watering but the effectiveness of WaterUps® depends on an efficient wicking material placed in legs. Gravel has the next greatest water capacity but due to it wicking only 114mm, almost half of the 200mm deep reservoir could not be used which would gave it approximately the same effective capacity as sand.

The percentage of water actually used from the reservoir in the wicking bed trials was not able to be measured for all treatments. The wicking beds had a clear plastic indicator tube attached to the reservoir that showed the water level of free water in the reservoir. This allowed measurements to be made for the gravel and WaterUps® treatments. For the sand and cocopeat treatments, the water level in the indicator tube dropped to zero in 19 - 28 days as the free water in the reservoir was used. Because field capacity of cocopeat and sand was high, these reservoirs would have still contained a large amount of available water even though the indicator tubes were empty. To measure the amount of water remaining in cocopeat and sand reservoirs, soil moisture sensors would have to be placed in the reservoir layers.

5.3 Growing medium

Once water moves out of the reservoir into the growing medium, it continues to rise by capillary action through the growing medium. So before examining the effect of different reservoir materials on the soil moisture in the growing layer, the capillarity of various growing media was examined.

The capillary rise tests performed on the soil mixes cannot be regarded as significant because only one replicate was conducted, however the differences recorded for the soil types were greater than the differences within the cocopeat mix and potting mix tests which demonstrates that further testing of the capillary rise properties of commercially available soil mixes is needed. The soil mixes were all various proportions of sand, silt, compost, manure and pine bark. The most expensive mix (Super soil) had the greatest capillary rise and the cheapest (Vegie mix) had the lowest capillary rise.

The cocopeat mix that was used in the wicking bed trials appeared to be a suitable medium for growing plants in wicking beds. Apart from the variation in growth rates between the inner and outer halves of the beds that occurred with spinach in WBT1, no growth problems that could be attributed to the growing medium were observed in either the spinach or lettuce plants. The variation in spinach plants between the bed halves also occurred in the beds using potting mix so the growing medium was not the cause of this variation.

Maximum capillary rise in the cocopeat mix was significantly more than in the potting mix (198 and 165mm). However, the capillary rise in both these media is within the reported range for media used in hydroponic growing, which have a capillary rise of 40-180mm in 48 hours (Kappel & Slezák, 2004). The cocopeat mix rose 131mm in 48 hours and the potting mix 121mm. The cocopeat mix was hydrophobic when dry and it was suspected that this reduced its wicking ability (Hallett & Gaskin, 2007; Letey, Osborn, & Pelishek, 1962). However, if the material was moistened before the experiment to make it less hydrophobic, it was not possible to observe the wetting front in the tube as there was no discernible colour change. A different experimental technique would be required to assess this. The potting mix was only able to sustain a capillary rise of greater than 5mm per day up to 162mm, significantly less than the cocopeat mix. This would suggest that the potting mix would be more suitable for shallower growing layers than the 250mm used in these trials.

The sand.cp and sand.pm treatments both used the same reservoir treatment but with different growing media (cocopeat mix and potting mix respectively), so comparison between these two treatments can be used as a comparison of the growing media performances. There was no difference in the plant weights in WBT2 between the sand.pm and sand.cp treatments, however in WBT1 the sand.pm treatment produced significantly less plant growth than sand.cp. The smaller capillary rise capability of the potting mix compared with the cocopeat mix was reflected in the soil moisture measurements. The potting mix was wetter than cocopeat mix at 200mm depth and drier at 100 and 50mm depth.

5.4 Plant growth

In the beds with cocopeat mix as the growing medium in WBT1, cocopeat and sand.cp grew the heaviest spinach plants and gravel the lightest. The weight of plants in potting mix with a sand reservoir (sand.pm) was less than all the other treatments. Cocopeat with a sand reservoir (sand.cp) also used the most water from the reservoir. There was a positive correlation between plant dry weight and amount of water used from the reservoir (r^2=0.7061), but no correlation between plant weight and minimum soil moisture or between water used and minimum soil moisture.

In WBT2, there was no significant difference in the weights of the lettuce between any of the treatments. As with the spinach trial, the cocopeat and sand.cp treatments used more water than gravel or sand.pm, although the WaterUps® treatment in WBT2 with sand as the wicking medium used the most water.

The potting mix in the sand.pm treatment had a lower EC than the cocopeat mix used in the other treatments which may have indicated a lower level of nutrients in the potting mix. However, a nutrient solution with EC of 1.4dSm^{-1} produced the best growth in hydroponically grown lettuces (Samarakoon, Weerasinghe, & Weerakkody, 2006), which is similar to the EC of the potting mix, and there was no difference between the ultimate weight of lettuces in the potting mix and cocopeat mix so the nutrient level of the potting mix was obviously adequate.

5.5 Soil moisture

The discussion above has described the potential for various reservoir materials to supply water to the growing layer of a wicking bed. How well this supply meets the needs of the growing plants is shown in the amount of moisture actually in the soil where the plants are growing. Soil water tension in the experimental wicking beds was between -6.5 and -65.9kPa (WBT1) and between -3.7 and -29.0kPa (WBT2). In hydroponic cropping soil water tension is usually above -8kPa, and -10 to -20kPa is considered dry while in open fields, soil is usually in the range -10 to -75kPa (Raviv & Lieth, 2008). The soils in the wicking beds were generally wetter than field soils but drier than hydroponic systems.

5.5.1 Soil moisture measured by tensiometer

Comparing tensiometer measurements between WBT1 and WBT2, most treatments in both experiments show a drying of the soil over time until the reservoirs were refilled which caused rehydration of the soil. However, there are differences between the experiments as well as some similarities.

Some of the differences in soil water tension between trials are:

- The soil in all treatments in WBT1 became much drier over a similar time period than in WBT2. This could have been due to differing water demands from a different crop (spinach vs lettuce) but was more likely due to a higher ambient temperature during WBT1 causing greater evapotranspiration.

- The sand.pm treatment was generally the wettest treatment in WBT1 but was as dry as the gravel treatment in WBT2. There was a large variation in soil moisture between the three sand.pm beds; in WBT1 two beds remained wet and one bed dried while in WBT2, two beds dried and 1 bed remained wet. This was probably due to poor and uneven wicking in the potting mix. The soil moisture measurements at different depths show that the potting mix at 200mm depth remained very wet while it was considerably drier at 100mm depth. With the tensiometer located at 150mm between these two depths, a small variation in wicking could lead to large differences in the tensiometer measurements.
- The soil in the WaterUps® treatment was almost as dry as gravel in WBT1 but was the wettest in WBT2. This would have been caused by improved wicking from changing the wicking material from perlite in WBT1 to sand in WBT2.

Some similarities in results between WBT1 and WBT2 provide support for drawing general conclusions about wicking bed performance:

- All treatments remained moist (above approximately -10kPa) at 150mm depth until about day 20 when soil moisture in some treatments started to decline. Both experiments were started with the soil at field capacity and until about day 20 capillary rise from the reservoirs was able to maintain this level of moisture. After this time, the increased evapotranspiration rate from the growing plants was greater than the capillary rise from some reservoir media.
- Beds that dried over time generally recovered soil moisture after the reservoirs were refilled. The cocopeat treatment in WBT1 did not recover much; two beds did but one bed continued to dry after refill. This may have been due to a problem with the tensiometer rather than a true difference in soil moisture because the plant weight from this bed was not affected .
- The soil in the gravel treatment started drying earlier and dried more than other treatments in both WBT1 and WBT2. This is in line with the capillary rise results that showed water in gravel rose less than cocopeat, sand or perlite.
- In both experiments, sand.cp dried about 2/3 as much as gravel.

- Cocopeat remained consistently wetter than either sand.cp or gravel.

Considering the results of both WBT1 and WBT2, the following observations can be made about each reservoir material tested:

cocopeat	Soil remained reasonably evenly moist (between -2.5 and -21.8kPa) throughout each experiment (excluding the anomalous drying of one bed in WBT1). This possibly indicates that the cocopeat mix is able to wick sufficient water to support the growing plants, although this treatment did not have geotextile between the reservoir and growing layers so it is possible that plant roots grew deeper than in other treatments and accessed water without it having to rise as far through the medium.
gravel	Soil moisture in gravel started falling earlier and dropped at a greater rate than other treatments even though there was water remaining in the reservoir. The capillary rise experiments showed limited capillarity in gravel and this resulted in the gravel reservoir being unable to sustain sufficient water supply to the plants for as long as the other reservoir media.
sand.cp	Soil became drier in sand.cp than cocopeat or WaterUps®, but not as dry as gravel. Capillary rise results indicated sand had a much greater capillary rise than cocopeat but the cocopeat reservoir held more water than the sand reservoir so the drying soil may have been due to water depletion in the sand reservoir. Another possible explanation is that root growth in cocopeat extended into the reservoir layer and there were fewer roots extracting water from the growing layer than in the sand.cp treatment. More investigation into patterns of root growth in wicking beds is warranted.
WaterUps®	The performance of WaterUps® is dependent on the wicking medium used. Medium grade perlite was not effective but sand resulted in the WaterUps® treatment having the highest average soil moisture this moisture was maintained reasonably evenly throughout the experiment.

WaterUps® with sand wicks maintained better soil moisture than a reservoir filled with sand. It would appear that WaterUps® are better than sand because once water starts to be used from the reservoir, the amount of free water in the sand reservoir drops quickly, while the columns of sand in the WaterUps® remain surrounded by free water. Thus there is a much greater tension gradient over a shorter distance with the WaterUps®, and Darcy's law (Hubbert, 1956) shows this will result in greater flow.

Although WaterUps® with sand as the wicking medium maintained a higher level of soil moisture compared with that provided by other reservoir treatments, the soil moisture was lower than is typically used in hydroponic growing systems. It would be interesting to determine if more or larger wicking columns in a free water reservoir could keep the soil moisture tension above -8kPa and improve plant growth rates.

5.5.2 Soil moisture at different depths

Soil moisture measurements were also made during WBT2 at 50, 100 and 200mm depths. Although there were considerable variations between the three moisture measurements made in the same bed at the same depth, comparison of twenty measurements in each bed with the preceding and following days showed that significant differences were rare and it was considered that the Pulse™ measurements were reliable enough to use. However, it is not known whether the variations that were observed were real variations in soil moisture at different locations within a bed, or variations in the accuracy of the Pulse™ meter. This needs more investigation. The meter manufacturer states that measurements may change over time with growth in roots and that in a commercial nursery setting the meter should be periodically recalibrated to provide accurate moisture results with a changed root density. That was not done during this experiment, but the average magnitude of variation between measurements did not change during the course of the experiment, so if increasing root density affected measurements, it affected them all equally.

There was only a moderate correlation between the Pulse™ and tensiometer measurements (r^2=0.4456 when comparing 150mm tensiometer values with the average of 100 and 200mm Pulse™ measurements) but the patterns of change in soil moisture are generally similar.

Semananda et al. (2020) found a steady increase in soil moisture with increasing depth in wicking beds. However, the watering regime reported for that study involved refilling the reservoir based on the calculation of overall soil moisture and the authors refilled the reservoirs more frequently than in this current study. This may have led to a more consistent moisture profile than was observed here.

In the current study the cocopeat and sand.cp treatments exhibited similar patterns of soil moisture variation over time, but in sand.cp the 200mm layer became drier than in cocopeat, and the sand.cp soil at 200mm became drier than the soil at 100mm. The moisture in the surface layer of cocopeat was much more variable than sand.cp. Although sand was shown to have better wicking ability than cocopeat, the cocopeat reservoir held 77% more water than the sand.cp reservoir and this greater amount of available water may be the reason why cocopeat remained wetter than sand.cp at 200mm depth.

Soil moisture in the gravel treatment was similar to cocopeat and sand.cp at 100mm depth but greatly different at 200mm depth. At day 24, when moisture measurements at 200mm depth were first made, the 200mm depth of the gravel treatment was drier than 50 or 100mm. The gravel treatment was significantly drier at 200mm than cocopeat or sand.cp. The soil moisture at 200mm in gravel remained lower than the soil above until the reservoirs were refilled. Although the gravel reservoir held more water than cocopeat, gravel exhibited very poor capillary rise compared to cocopeat or sand. The low soil moisture in the gravel treatment would be caused by lack of water movement from the reservoir to the growing medium by capillary rise in the gravel.

The beds with WaterUps® had the greatest soil moisture at 100mm depth. Moisture at 50mm depth was highly variable, but was always significantly drier than 100mm depth. From day 15 to day 35, the 50mm layer became wetter, in contrast to other treatments where this depth dried out. It may be possible that evaporation from soil surface reduced as plant canopy covered surface, but plant canopy spread in WaterUps® was no different to other treatments. It is possible that a greater supply of water from the WaterUps® reservoir compared to other treatments meant more water rose to the surface to be evaporated. This could be tested with a comparison of mulched and unmulched beds. Surface mulching of wicking beds can increase surface soil moisture by 10-15% and lead to better water use efficiency due to lower evaporation (Semananda et al., 2020).

In all treatments after refilling the reservoir the soil at all depths became wetter. In all treatments except WaterUps®, the soil moisture at 200mm started to decline again after rehydration while the soil above was still becoming wetter. The distribution of roots within the growing medium was not investigated, however it is possible that with higher moisture in the lower region of the growing medium after planting the plant roots quickly grew down to 200mm depth. A greater number of roots at this depth would remove more water from this region. If capillary rise from the reservoir was insufficient to replenish this moisture, the 200mm depth would become drier than the layers above. Lettuces grown in wicking beds by Semananda et al. (2020) grew the majority of their roots in the top 100mm, but these seedlings were top watered every three days for the first three weeks which would have encouraged development of surface roots. The seedlings in the current study were top watered only three times in the first four days which may have encouraged root growth to greater depths.

After refilling the reservoir, none of the 50 or 100mm layers recovered to the moisture levels recorded at the start of the experiment when moisture was at field capacity. In all treatments except gravel, the soil moisture at 200mm depth (which is 50mm above the top of the reservoir) rose to close to field capacity after refilling. Capillary rise does not appear to have sufficient flow in wicking beds to maintain soil 150mm or more above top of reservoir at field capacity in beds with lettuce plants approaching harvest maturity. A longer term study with plants that require several reservoir refills during their life may shed more light on the movement of water through the growing layer of a wicking bed. The current results suggest that overall soil moisture may either drop over time or become steady at a lower level. This may reduce the long term productivity of wicking beds.

As observed earlier, the potting mix used in the sand.pm treatment remained wetter than all other treatments at 200mm depth while at 50mm was significantly drier than other treatments and did not recover moisture after refill. This indicates that the capillary rise in the wicking potting mix was poor and that this type of potting mix is likely to be better suited to shallower wicking beds, or that transplanted seedlings will need to be top watered until their roots grow down to the available soil moisture.

5.5.3 How often to refill wicking beds

One frequently asked question about wicking beds is how often they need to be refilled. Semananda et al. (2020) added water to the reservoir every two weeks and the amount added was derived by a calculation based on the change in soil moisture measurements. However, the common practice (and the one adopted in this study) is to refill the reservoir when needed until it overflows. Semananda et al. (2016) filled the reservoirs when soil moisture dropped to 75% of field capacity but did not report how frequently this occurred. In popular literature, suggestions of watering every one or two weeks are frequently given. Based on the current study, if a minimum soil water tension of -20kPa is used for growing leafy greens in wicking beds, then gravel reservoirs would require refilling every 30 days and sand reservoirs every 35 days. Cocopeat and WaterUps® reservoirs should be able to sustain a higher soil moisture for longer, but how much longer is not known from this study. The length of time between refills will also be affected by the weather conditions and ET_c of the crop and may differ somewhat from the results of this study. However, there is a strong indication that wicking beds do not need to be refilled as often as is commonly believed.

5.5.4 Plant water use

The lettuce in WBT2 used less water than has been reported by others. Lettuce requires a minimum of 400L/kg dry weight to avoid tip burn (Both, 1995). Water use in WBT2 ranged from 202L/kg (sand.pm) to 335L/kg (WaterUps®). Some plants in all treatments experienced some tip burn on the outer leaves. Average water use efficiency in WBT2 based on dry weight (4.22g/L) is similar to the best WUE (4.02g/L) in hydroponic lettuce (Montesano et al., 2016). However, WUE based on wet weight (85.1 - 123.6g/L) is much greater than WUE for wicking bed lettuce in Semananda et al. (2020) (12.8 - 23.3g/L). Lettuces grown in a closed hydroponic system weighed 134-157g/plant with water use of 12.6-14.4litres/kg (Kratky, 1993). The lettuce in the current study had an average weight of 486g/plant and with water use of 8.3 - 12.0L/kg.

The current study was not focussed on growing the highest quality plants; instead it was designed to investigate water movement from the reservoir and purposefully stressed the plants by allowing the soil to dry as water supply from the reservoirs dropped. If water was added to the reservoirs more frequently the quality of plants may have been higher and water use results may have been closer to those found in other studies. However, even the WaterUps® beds, which had the highest overall soil moisture and their reservoirs never ran out of water, suffered some tip burn.

Tip burn in lettuce is caused by a localised calcium deficiency in rapidly growing leaves (Hartz, Johnstone, Smith, & Cahn, 2007). While a shortage of water may play a part in producing tip burn, it is likely to be caused by insufficient transpiration, rather than a lack of soil moisture. Reducing humidity or increasing airflow over the leaves can reduce tip burn (Goto & Takakura, 1992; Wien & de Villiers, 2005). Daytime humidity within the polytunnel during WBT2 was consistently around 90%. Although doors at both ends of the polytunnel were usually open there was no forced air movement or other ventilation provided. Thus it cannot be concluded that lack of moisture supply from any of the wicking bed treatments were responsible for causing tip burn. Measures to provide additional ventilation and reduce daytime humidity within the polytunnel would likely have reduced the incidence of tip burn.

5.6 Wicking bed size

The main aim of WBT3 was to investigate the effect of a geotextile layer between the reservoir and growing media. WBT3 used small wicking beds (0.063m^2 area) with a single lettuce plant growing in each bed; WBT1 and 2 used larger wicking beds (0.55m^2 area) growing 12 plants/bed.

The small wicking beds produced significantly larger lettuces than the large wicking beds. The small wicking beds had 37% more soil volume per plant than large wicking beds. This may account for the greater plant growth. Although the smaller beds used more water than the larger beds, there was no significant difference in plant water use (L/g) between the two.

The common treatment between WBT2 and WBT3 was with cocopeat in both the reservoir and growing layers with no geotextile between the layers (called cocopeat in WBT2 and cp.none in WBT2). The comparison of this treatment between the large and small beds was the same as comparing all treatments; the small beds grew larger lettuces and used more water but had the same plant water use.

The patterns of variation in soil moisture over time were very similar at all depths for the cocopeat (large beds) and cp.none (small beds) treatments. There were no significant differences in the minimum soil moisture levels measured between the two experiments for this common treatment.

Thus it is valid to compare soil moisture and water use effectiveness results across these two wicking bed sizes. It also shows that the smaller wicking beds will be suitable for conducting future wicking bed experiments at a much lower cost and smaller space usage than the larger wicking beds.

5.7 Effect of geotextile separating reservoir and growing medium

Because the cocopeat treatment in WBT1 and WBT2 did not use a geotextile between the reservoir and growing layers but the sand and gravel treatments did, it was important to investigate whether the presence or absence of geotextile affected the operation of wicking beds. WBT3 used cocopeat treatments both with and without geotextile (cp.gtex and cp.none) and a sand reservoir without geotextile (sand.none).

There was no difference in the amount of water used by cp.none and cp.gtex, nor any difference in the plant weights. From this it can be concluded that geotextile makes no difference to the wicking, at least when the reservoir and growing layers contain the same medium.

Sand.none used significantly less water than the other two treatments but produced plants of the same weight. In WBT1 and WBT2, sand.cp (with geotextile) also used less water than cocopeat, but in these experiments the difference was not significant ($P>0.05$). This result provides some, but not conclusive, support for the findings of Sullivan et al. (2015) that presence or absence of geotextile makes no difference in wicking beds.

A geotextile layer separating the growing and reservoir media is often used in wicking beds to prevent the growing media moving into the reservoir layer and filling pore spaces that could otherwise be filled with water. This effect was not tested in the current study, but these results show that the presence of a geotextile layer is unlikely to have any significant effect on water movement withing a wicking bed. However, this may depend on the particular media used in the reservoir and growing layer. There are reports that a geotextile layer can form a capillary barrier especially when under fine grained soils due to differences in pore sizes (Azevedo & Zornberg, 2013; McInnes & Thomas, 2012) but this was not observed in the wicking beds.

5.8 Electrical conductivity

In agricultural and horticultural systems it is common to occasionally apply excess irrigation to the soil surface to leach away salts that accumulate on the surface due to evaporation. Wicking beds are only watered from below, so it is possible that salts will build up on the surface over time.

Only the WaterUps® treatment in WBT2 experienced a rise in EC in the upper soil layer. EC in all other treatments declined, presumably as a result of the plants consuming nutrients from the soil. The average soil moisture at 50mm depth was slightly higher in the WaterUps® treatment than other treatments, but not significantly so. There may have been higher evaporation from the surface of the WaterUps® beds leading to the increase in EC, but there is not convincing evidence from this study that salt build up is a problem in wicking beds.

The average maximum EC level recorded across all treatments was 2.55 dSm^{-1} with an absolute maximum of 2.85 dSm^{-1}. Since yields of most crops are not restricted until EC rises to 4-8 dSm^{-1}, the EC levels recorded during this study would not have had a detrimental effect on plant growth.

6 Conclusion

Prior to this study, the limited research that had been published about wicking beds had focussed mainly on comparing the efficiency of wicking beds with conventional top watered containers. Little had been done to investigate the effects of different media in the reservoir and growing layers of wicking beds. This study has started addressing that gap, and has developed and tested several tools suitable for the collection of performance related data, including moisture, temperature and EC, that can be easily implemented in an urban wicking bed production system.

The initial hypothesis was that the choice of reservoir material for a wicking bed would affect plant growth and moisture distribution within the growing medium. Different reservoir materials did result in variable growth in spinach but not lettuce, and soil moisture differed between several treatments in all experiments. Thus the hypothesis is largely supported, although effects on plant growth may vary depending on the crop being grown.

The capability of a material used in the reservoir layer of a wicking bed to support capillary rise of water is fundamental to how well the wicking bed performs. This study confirms findings in the literature that capillary rise is greater in finer materials than coarse materials. Of the materials tested, capillary rise was greatest in crusher dust, followed by sand. 10mm crushed gravel had limited capillary rise and scoria, a material commonly specified for reservoirs in wicking beds, had very small capillary rise. Maximum capillary rise in a mix of cocopeat, compost and sand was about two thirds of the rise in washed sand and almost twice the rise in crushed gravel.

Materials with larger particles had a greater pore space and could store more water in the reservoir layer of a wicking bed. Gravel held more water than sand which held more than crusher dust. Test results indicated that the cocopeat mix had the ability to store the most water of any material tested due to its ability to absorb water within the cocopeat and compost particles, but in the greenhouse trials the cocopeat mix held the same amount of water as gravel, probably due to greater compaction of the material in the wicking bed.

Coarse materials such as gravel or scoria are a poor choice for reservoir unless the reservoir is shallow. 10mm gravel was able to wick water up approximately 100mm, but as the water level in the reservoir dropped towards this level there was insufficient water flow to maintain adequate soil moisture in the growing medium. Sand or cocopeat are better choices for a reservoir material and provide greater soil moisture but there remain questions about whether cocopeat is suitable for long term use in a saturated state.

WaterUps® provided a greater volume of water in the reservoir than other materials and could maintain higher and more uniform soil moisture levels over time than other reservoir treatments, but were reliant on use of an appropriate wicking material. WaterUps® with medium grade perlite performed poorly and resulted in low soil moisture levels but high soil moisture levels were maintained when using sand as the wicking medium.

While there was no difference between treatments in the weight of lettuces, the effects of reservoir material on soil moisture may also have implications for longer term crops or successive crops if the growing medium is not rehydrated between cropping cycles. In all treatments, the soil moisture in the middle and upper layers of the growing medium did not return to their starting levels after the reservoirs were refilled. Further research is needed to determine if this drying trend continues over several reservoir refills or if the soil moisture at upper levels stabilises over time. If soil moisture is concentrated in the lower levels of the growing medium, this may affect nutrient availability for a longer term crop.

The choice of growing medium can also affect water movement and plant growth in a wicking bed. Cocopeat mix maintained more consistent soil moisture levels across depths than the potting mix and grew significantly heavier spinach plants. In the potting mix, soil moisture was high at the bottom of the growing medium but upper levels were dry. The cocopeat mix was a better growing medium for wicking beds than the commercial potting mix that was used.

There was no strong evidence of a build-up of salts on surface of any of the wicking beds, but the possibly that it could be a problem in the longer term cannot be ruled out by this study.

Large variations in moisture readings were observed within beds and this introduced a level of uncertainty to the results. Only three replicates of each treatment were used in this study which may not have been enough to provide a high level of confidence in the results. Further trials with more replicates would increase the level of confidence in the results.

While the outcomes of this current research provided some insight into wicking bed design and utility, there remain several areas that should be explored by further research including:

- can wicking beds raise soil moisture to levels similar to that of hydroponic systems and will this boost productivity?
- what is the best way to determine when to add more water to the reservoir?
- can the tools developed (electronic tensiometers and Arduino based data logging) and utilised (Pulse^{TM} moisture/EC probe) be relied on consistently for both research and production. For example, are the variations in Pulse^{TM} readings across one bed due to real variations in moisture across the bed or are they variations in measurement?
- how long can a cocopeat mix be used in the reservoir layer before it decomposes and becomes detrimental to the system?
- can wicking beds be used in the long term as an organic system relying on compost and nutrient cycling for plant nutrition and encouraging growth of mycorrhizal fungi and other soil biota instead of operating them more like hydroponic systems and relying on manufactured fertilisers?

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Appendix 1 - Selection of wicking bed designs from popular literature

Source	URL	Design type	Reservoir media	Reservoir depth	Fabric	Growing media	Growing depth	Comment
VEG - Very Edible Gardens	https://www.wickingbeds.com.au/make-wicking-bed/	horizontal layers	7mm or 1/4inch bluestone screenings (quarter minus)are the ticket, or pea gravel	150-200+ mm	geotextile or double shade cloth	fairly porous loam that is not too heavy in clay or organic matter, a sandy loam with moderate organic matter, ask for a good organic mix for veggies	250-400mm	
The Little Veggie Patch Co	https://littleveggiepatchco.com.au/blogs/news/building-a-wicking-bed	horizontal layers with wicks of geotextile	fine grade scoria (the finer the grade of scoria, the better)	250mm	geotextile	soils that have high levels of organic matter and compost, add 1 part perlite to 10 parts soil	250mm	
Gardening Australia	https://www.abc.net.au/gardening/factsheets/building-a-wicking-bed/9435452	horizontal layers	scoria, gravel or another aggregate	200mm	Geotextile or old shade cloth	good quality vegie garden soil that's high in organic matter	300mm	
Permaculture Research Institute	https://permaculturenews.org/2011/06/20/from-the-bottom-up-a-diy-guide-to-wicking-beds/	horizontal layers	gravel	<= 300mm	landscape fabric	high carbon soil, a combination of loam, compost and peat	300-320mm	
Sustainable Gardening Australia	https://www.sgaonline.org.au/wicking-beds/	horizontal layers with soil extending down into reservoir	15cm gravel or scoria then 15cm soil blend (saturation layer)	300mm	geotextile on top of scoria layer	good quality soil/compost blend, 1/2 mushroom compost and 1/2 organic soil mix	300mm	wicking beds work best with a higher than usual compost portion
Deep Green Permaculture	https://deepgreenpermaculture.com/diy-instructions/wicking-bed-construction/	horizontal layers	coarse scoria	200mm	geotextile or shade cloth	high grade soil with a good level of organic matter; a mix of 50% premium soil, 25% organic compost and 25% organic cow manure	400mm	

Source	URL	Design type	Reservoir media	Reservoir depth	Fabric	Growing media	Growing depth	Comment
Green Life Soil Co	https://www.greenlifesoil.com.au/sustainable-gardening-tips/wicking-beds	horizontal layers	fine bluemetal or gravel, coarse woody mulch (eg. tree prunings) or coarse river sand (If using stones or gravel, use small ones)	200mm	geotextile or shade cloth	good, friable organic vegetable mix	200-300mm	
Sophie's Patch	https://sophiespatch.com.au/2018/01/26/wicking-bed-trouble-shooting/		not blue metal or crushed limestone (very alkaline)		none	Wicking only works when the soil is high in organic matter; good quality commercial vegie garden soil and then add about 1/3 to 1/2 more compost to it		update on ABC Gardening Australia designs; not mushroom compost - very alkaline
Urban Food Garden	https://www.urbanfoodgarden.org/main/wicking-beds/wicking-beds.htm	horizontal layers	25mm scoria; 20mm bluestone	90mm	non-woven weed mat	light friable soil	310mm	
Gaia's Organic Garden	http://www.gaiasorganicgardens.com.au/how-to-make-wicking-bed/	horizontal layers	porous stone, such as pea gravel	150-200mm	geotextile, old sheets or fabric	soil mix with good drainage	250mm	tuck fabric into sides so that it creates a neat and secure layer
Urban Agriculture Australia	http://www.urbanagriculture.org.au/information/design-systems/building-a-wicking-bed/	horizontal layers	washed river sand, 6mm road base, pea shingle, scoria, straw or autumn leaves, or similar	<= 300mm	geotextile or sugar cane mulch	lightweight free draining vegetable mix, sandy loam, compost (or mixture)		
Sustainable Gardening Australia	https://www.sgaonline.org.au/sustainable-wicking-worm-bed/	horizontal layers	aged pine bark chips	300mm	shade cloth	good soil		
Milkwood Permaculture	https://www.milkwood.net/2010/05/11/how_to_make_a_wicking_bed/	horizontal layers	gravel	300mm	none		300mm	
SBS (Costa)	https://www.sbs.com.au/shows/costa/listings/detail/i/1/article/6172/wicking-garden-beds	horizontal layers with plastic voids in reservoir	washed river sand		geotextile	lightweight planter mix		sand to bottom of reservoir around and over plastic tanks

Source	URL	Design type	Reservoir media	Reservoir depth	Fabric	Growing media	Growing depth	Comment
Better Homes and Gardens	https://www.bhg.com.au/how-to-make-a-wicking-bed-trough	horizontal layers	20mm scoria	200mm	geotextile	potting mix	270mm	
ABC Organic Gardener	https://www.organicgardener.com.au/articles/creating-wicking-bed	horizontal layers	gravel	100mm	hessian bag	organic potting mix, compost, worm castings and minerals	200mm	small wicking bed in polystyrene box
Medium	https://medium.com/@rosseyre/how-to-build-a-wicking-bed-version-2-0-f5ddf52f4d57	horizontal layers	stones/gravel	<= 300mm	builders fabric	high quality organic compost, loamy soils, peat, etc.	<= 400mm	growing media to 10-20cm below overflow; uses toilet cistern with float to keep reservoir full - use 100mm reservoir depth
Permaculture College Australia	https://permaculture.com.au/water-saving-wicking-bed/	horizontal layers	50+mm rocks to ~70mm then gravel	200mm	old shade cloth	100mm layer woodchips then mix of compost, crushed basalt, sand, soil, crushed biochar	350mm	
My Smart Garden	https://www.mysmartgarden.org.au/Resources/Water/Build-a-wicking-bed	horizontal layers	7mm bluestone screenings	150mm	geotextile fabric or doubled shade cloth	fairly porous loam that is not too heavy in clay or organic matter	250mm	
Simple Savings	https://www.simplesavings.com.au/p/How-to-make-an-IBC-Wicking-Bed	horizontal layers	5-7mm screenings		weed mat	30% compost, 70% loam		
Colin Austin	www.waterright.com.au/wicking_%20bed_technology.pdf	horizontal layers	Wood chips	200mm	none	Soil	200-300mm	
Canberra Permaculture Design	http://www.canberrapermaculturedesign.com.au/wicking-beds.html	horizontal layers	gravel or scoria, crushed bricks or sand, or a combination <10mm dia	1/4 height of bed eg 100mm	geotextile	well-rotted down compost and sand; potting mix	eg 300mm	
EcoFilms	http://www.ecofilms.com.au/create-a-wicking-bed-garden-for-easy-vegetable-	horizontal layers	vermiculite; coconut coir fibre	90mm	none	good potting mix	300mm	

Source	URL	Design type	Reservoir media	Reservoir depth	Fabric	Growing media	Growing depth	Comment
	growing-powered-by-fishwater/							
My Home Harvest	http://myhomeharvest.com.au/newmhh/wicking-bed-project/	horizontal layers	scoria	150mm	shade cloth	good quality soil, compost and potting mix	200mm	
Goodlife Permaculture	https://goodlifepermaculture.com.au/a-wildlife-proof-no-dig-garden-wicking-bed/	horizontal layers	7-20mm blue metal	200mm	geo-fabric	no-dig layers - straw, aged chook poo	400mm	
Verge Permaculture	https://vergepermaculture.ca/2011/05/30/guide-to-wicking-beds/	horizontal layers	28mm washed rock	300mm or less	high grade landscape fabric	high carbon soil	300-320mm	
Mindarie Regional Council	https://www.mrc.wa.gov.au/School-community/Fact-Finding-Information/Wicking-Bed	horizontal layers	broken bricks and sand or flowerpots stuffed with old t-shirts		old carpet or shade cloth	soil/compost		
Permaculture West	www.willettongarden.org.au/wp-content/uploads/R5-pw-wicking-beds.pdf		blue metal, gravel, crushed brick, or even coarse mulch	300mm	shade cloth, geotextile, carpet, old sheets etc	good quality organic soil that's a bit coarse	300mm	
Hume City Council	https://www.hume.vic.gov.au/files/sharedassets/hume_website/environment/live_green_-_get_involved/gardening_fact_sheets/gardening_fact_sheets_amp_books/wicking_garden_bed_fact_sheet.pdf	horizontal layers	7mm gravel or sand	200mm	70% shade cloth or geotextile	Garden soil, blended with compost	400mm	

Source	URL	Design type	Reservoir media	Reservoir depth	Fabric	Growing media	Growing depth	Comment
Tasman Ecovillage	https://tasmanecovillage.org.au/happenings/news/301-wicking-bed-guide	horizontal layers	sand & scoria/limestone or other porous stone/rock	200mm gravel + 200mm soil	geotech fabric	improved soil (soil+chicken manure+compost)	200mm	
Living Fundraisers	https://livingfundraisers.com.au/wp-content/uploads/2016/05/Wicking-Bed-Activity-Sheet.pdf	horizontal layers	scoria (stones)		geotech fabric	good quality vegie growing soil	300-400mm	
Sustainable Education	https://sustainableeducation.com.au/sustainable-living/wicking-beds/	horizontal layers	gravel or scoria	300mm	geotextile fabric	good quality well-draining loamy soil with high organic content	300mm	
Permaculture Central Coast	https://permaculturecc.org.au	horizontal layers	lightweight rocks, or gravel + plastic pots for voids	<= 300mm	weed matting/ geotech fabric/ shade cloth	soil high in organic matter	300mm	

Appendix 2 - Arduino code for data logger

```
//************************************
// Read voltages of 8 tensiometers thru MUX
// write data to SD card
// and display the data on the monitor
//
// There are two versions of this code defined by LOGGER_ID
//    1 has temperature/humidity sensors, 2 does not
// Chris Curtis 24/10/2019
//
// 20/2/20 - added code to read temperature/humidity sensor
// 20/2/20 - added LOGGER_ID to output string
//**************************************

#include <math.h>
#include <Wire.h>
#include <SparkFunDS1307RTC.h>  // for rtc
#include <SPI.h>  // for sd card
#include <SD.h>   // for sd card
#include "DHT.h"

//#define LOGGER_ID 1     // monitors beds 1-8 and includes
temperature/humidity sensor
#define LOGGER_ID 2  // monitors beds 9-16 (no temperature/humidity sensor)

#define NUM_READS 11    // Number of sensor reads for filtering
#define FIRST_BED 1
#define LAST_BED 8
#define FILE_NAME "tensio2.csv"
#define DHTPIN 15     // Digital pin connected to the DHT sensor (A1)
#define DHTTYPE DHT11   // DHT 11

const String version = "soilMoisture v1.4";

String currentTime;
int i;
int bedId;
int tensVal[9]; // median values from tensiometers - use [1] thru [8], [0] not
used
int rawVal[NUM_READS];
float temperature1; // temperature from LM35 sensor
byte dat[5]; //data from temperature/humidity sensor
boolean readNow = true;
File myFile;
const int chipSelect = 4;
float h,t; // fro humidity and temperature readings

// Initialize DHT temperature/humidity sensor.
DHT dht(DHTPIN, DHTTYPE);

// set interval between readings (3600,000 ms = 1 hour)
// const unsigned long sleepTime = 10000L;
const unsigned long sleepTime = 3600000L;

unsigned long previousMillis = 0;

void setup() {
  // initialize serial communications at 9600 bps:
  Serial.begin(9600);
  Serial.println(version);
  Serial.println("Initialising...");

  // initialise the real time clock
  rtc.begin();

  // initialise ten temp/humidity sensor
  dht.begin();

  // initialise the SD card
  Serial.print("Initializing SD card...");
```

```
  pinMode(SS, OUTPUT);
  if (!SD.begin(chipSelect)) {
    Serial.println("initialization of SD card failed!");
    return;
  }
  Serial.println("initialization of SD card done.");

  // initialize the mux addressing digital pins as an output.
  pinMode(6, OUTPUT);    // S0
  pinMode(7, OUTPUT);    // S1
  pinMode(8, OUTPUT);    // S2
  pinMode(9, OUTPUT);    // S3

  // initial read of sensors so data is ready when requested
  //readSensors();

  Serial.println("Ready!");
}

void loop() {
  unsigned long currentMillis = millis();

  // only run code if sleeptime has elapsed
  if ((currentMillis - previousMillis >= sleepTime) or (previousMillis == 0))
{
    // save the last time the loop ran
    previousMillis = currentMillis;

    // read 8 tensiometers
    readTensiometers();
    temperature1 = readTemp();
    if (LOGGER_ID == 1) {
      // Reading temperature or humidity takes about 250 milliseconds!
      // Sensor readings may also be up to 2 seconds 'old' (its a very slow
sensor)
      h = dht.readHumidity();
      // Read temperature as Celsius (the default)
      t = dht.readTemperature();
    }

    // write results to SD card
    saveReadings();
    // display results on monitor
    displayReadings();

  } // end of  if currentmillis...

} // end of loop()

// *********************************
// for each bed, read the sensor multiple times then use the median value
// *********************************
void readTensiometers() {
  // get time from RTC
  rtc.update();
  currentTime = String(rtc.date()) + "/" + String(rtc.month()) + "/"  +
String(rtc.year()) + "," + String(rtc.hour()) + ":" + String(rtc.minute()) +
":" + String(rtc.second());

  for (bedId=FIRST_BED; bedId<=LAST_BED; bedId++) {
    setupMux(bedId);

    for (i=0; i<NUM_READS; i++) {
      rawVal[i] = analogRead(7);
      delay(5);
    } // end of multiple read loop

    // use median value from multiple reads
    sortReadings();
    tensVal[bedId] = rawVal[NUM_READS/2];

  } //end of bed loop
}  // end of  readTensiometers()
```

```
// ********************************

// set up multiplexor to read from specified input
// ********************************
void setupMux(int bedId) {
  // mux addressing
  //  i  S0  S1  S2  S3
  // 14  0   1   1   1  - bed 1
  // 13  1   0   1   1  - bed 2
  // 12  0   0   1   1  - bed 3
  // 11  1   1   0   1  - bed 4
  //  1  1   0   0   0  - bed 5
  //  2  0   1   0   0  - bed 6
  //  3  1   1   0   0  - bed 7
  //  4  0   0   1   0  - bed 8

  int S0 = 6;
  int S1 = 7;
  int S2 = 8;
  int S3 = 9;

  switch (bedId) {
    case 1:
      digitalWrite(S0, LOW);
      digitalWrite(S1, HIGH);
      digitalWrite(S2, HIGH);
      digitalWrite(S3, HIGH);
      break;

    case 2:
      digitalWrite(S0, HIGH);
      digitalWrite(S1, LOW);
      digitalWrite(S2, HIGH);
      digitalWrite(S3, HIGH);
      break;

    case 3:
      digitalWrite(S0, LOW);
      digitalWrite(S1, LOW);
      digitalWrite(S2, HIGH);
      digitalWrite(S3, HIGH);
      break;

    case 4:
      digitalWrite(S0, HIGH);
      digitalWrite(S1, HIGH);
      digitalWrite(S2, LOW);
      digitalWrite(S3, HIGH);
      break;

    case 5:
      digitalWrite(S0, HIGH);
      digitalWrite(S1, LOW);
      digitalWrite(S2, LOW);
      digitalWrite(S3, LOW);
      break;

    case 6:
      digitalWrite(S0, LOW);
      digitalWrite(S1, HIGH);
      digitalWrite(S2, LOW);
      digitalWrite(S3, LOW);
      break;

    case 7:
      digitalWrite(S0, HIGH);
      digitalWrite(S1, HIGH);
      digitalWrite(S2, LOW);
      digitalWrite(S3, LOW);
      break;

    case 8:
```

```
      digitalWrite(S0, LOW);
      digitalWrite(S1, LOW);
      digitalWrite(S2, HIGH);
      digitalWrite(S3, LOW);
      break;

    default:
      digitalWrite(S0, LOW);
      digitalWrite(S1, LOW);
      digitalWrite(S2, LOW);
      digitalWrite(S3, LOW);
      break;
   }
    delay(10);
}  // end of setupmux()

// *********************************
// sort array of values read so that the median value can be found
// *********************************
void sortReadings() {
  int j;
  int tempVal;
  for(i=0; i<NUM_READS-1; i++)
    for(j=i+1; j<NUM_READS; j++)
      if ( rawVal[i] > rawVal[j] ) {
        tempVal = rawVal[i];
        rawVal[i] = rawVal[j];
        rawVal[j] = tempVal;
      }
}  //end of sort()

// *********************************
// save readings from tensiometers to sd card
// *********************************
void saveReadings() {
  myFile = SD.open(FILE_NAME, FILE_WRITE);
  if (myFile) {
    myFile.print(String(LOGGER_ID) + "," + String(currentTime) + "," +
String(tensVal[1]) + "," + String(tensVal[2]) + "," + String(tensVal[3]) + ","
+ String(tensVal[4]) + "," + String(tensVal[5]) + "," + String(tensVal[6]) +
"," + String(tensVal[7]) + "," + String(tensVal[8]) + "," +
String(temperature1));
    // add humidity (%) and temperature (degrees C)
    myFile.print (',');
    myFile.print (String(h)); // display the humidity
    myFile.print (',');
    myFile.println (String(t)); // display the temperature

    myFile.close();
  } else {
    Serial.println(String(currentTime) + " Write to sd card failed");
  }
}  // end of save

// *********************************
// display readings on monitor
// *********************************
void displayReadings() {
  Serial.println(String(currentTime) + "," + String(tensVal[1]) + "," +
String(tensVal[2]) + "," + String(tensVal[3]) + "," + String(tensVal[4]) + ","
+ String(tensVal[5]) + "," + String(tensVal[6]) + "," + String(tensVal[7]) +
"," + String(tensVal[8]) + "," + String(temperature1));
  Serial.print ("Current humdity = ");
  Serial.print (String(h)); // display the humidity
  Serial.println ('%');
  Serial.print ("Current temperature = ");
  Serial.print (String(t)); // display the temperature
  Serial.println ('C');

}

// *********************************
// read TMP35 temperature sensor
```

```
// 10mV/degC with 500mV offset
// actual voltage supplied to sensor is 4.74V
// ********************************
float readTemp() {

  int sensorVal;
  float degC;

  sensorVal = analogRead(2);
  degC = ((4.740 / 1024 * sensorVal) - 0.5) * 100;
  return degC;
}
```