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RESEARCH ARTICLE

Estimating Unsaturated Hydraulic Conductivity of Cocopeat-Perlite Mixtures Using RETC Software

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ABSTRACT

Cocopeat in soilless culture needs to be mixed with other coarser substrates to increase the aeration medium. Hydraulic conductivity measures the ability of a fluid to flow through pore spaces under both saturated and unsaturated conditions. This study focused on estimating cocopeat-perlite unsaturated hydraulic conductivity using RETC software. Six (6) treatments were used, 100% cocopeat act as control treatment (T1), while treatments with different cocopeat-perlite ratios (T2=3 cocopeat:1 perlite; T3=2 cocopeat:1 perlite; T4=1 cocopeat:1 perlite; T5=1 cocopeat:2 perlite; T6=1 cocopeat:3 perlite) has been used for cocopeat-perlite unsaturated conductivity determination. Results obtained were compared using van Genuchten–Mualem model (VGM), van Genuchten–Burdine (VGB) and Brooks-and-Corey model (BC) with RETC software. As the perlite ratio increases, the rate of change in hydraulic conductivity also rises due to enhanced substrate porosity, thereby improving aeration around plant roots. T2 and T3 served as aeration improvement for cocopeat medium without rapid water loss in crop cultivation. In comparing results in BC and VGM, the derivation of hydraulic conductivity increases as approaches the saturation point. However, to obtain accurate results when n is larger than 2, the VGM was preferable due to no bubbling pressure effect that may result in discontinuity near slopes at saturation point. Thus, by understanding the effects on the cocopeat-perlite ratio, the substrate properties can be optimized to balance water retention and aeration according to specific horticultural needs. The ability to improve root zone aeration without compromising water availability highlights the potential of tailored cocopeat-perlite mixes to encourage greater crop yields in controlled environment agriculture.

1. INTRODUCTION

Irrigation is one of the most vital aspects that ensures that the crop receives adequate water throughout its growth stages. Water uptake during evapotranspiration supports other necessary functions such as photosynthesis, nutrient uptake, and overall plant development. The non-uniformity of precipitation distribution throughout the world presents difficulties in supplying the amount of water needed for irrigation. Coupled with the effects of climate change, countries on drier continents that rarely receive rainfall such as West Asia and North Africa face severest water poverty across the globe (Hashemi et al., 2016). Therefore, providing water to crop is a major issue that growers are aiming to address to get the highest water usage and application efficiency (Ilahi, 2017). Increasing water efficiency is also attributed to the pressure to provide water for environmental use as well as to reduce poverty and contribute to the growth of the economy (Molden et al., 2010).

To address the challenges posed by water scarcity, soilless culture medium emerges as a viable and sustainable substitute for the conventional method of soil-based agriculture. Aside from mitigating challenges in the agriculture system such as drought and resource degradation, soilless culture system development is advancing due to an increase in population awareness towards the consumption of agricultural products (Putra & Yuliando, 2015). The usage of soilless culture has also been proven to show beneficial effects compared to culturing in direct soil (Bhardwaj, 2014; Fontana & Nicola, 2009). Soilless culture has been utilized too as a solution for soil-borne disease, soil salinity, and infertile soil (Bougoul et al., 2005).

In soilless cultivation, plants are grown without soil using various inert or organic substrates to support root systems while providing water and nutrients through controlled irrigation. One of the most popular media used in soilless culture systems is cocopeat. The byproduct from the coconut production industry is commonly used as an alternative to peat (Cresswell, 2002). The organic material is comprised of short and long fibrous coconut husk and coconut dust. The physical and chemical properties have been proven suitable to be used as a substrate for soilless culture (Abad et al., 2002). Cocopeat exhibits high water-holding capacity, however, this character in some conditions cannot provide adequate aeration for plant roots. Another popular choice of substrate, pearlite has notable capabilities to increase aeration and water flow in the medium. This naturally occurring volcanic rock has large particles and low water-holding capacity. It is also physically stable and chemically inert in neutral pH, making it suitable to be used as an addition for substrates.

The choice and ratio of these substrates can influence water movement within the root zone which will significantly impact the plants' potential growth. Hydraulic conductivity, which refers to the measurement of fluid ability to flow through pore spaces and fractures in the presence of an applied hydraulic gradient of a material; provides insight regarding the water and nutrient distribution. Knowledge of hydraulic conductivity is important to properly design the irrigation system, and avoid water stress and fertilizer management (Londra, 2010). Various ratios of cocopeat-perlite mixture have been made for aeration improvement, for example, 1 cocopeat: 3 perlite, 2 cocopeat: 2 perlite, and 3 cocopeat: 1 perlite. However, studies by both Ilahi (2017) and Londra (2010) show that the mixture of 3 cocopeat: 1 perlite has shown to have the best hydraulic properties compared to other mixtures.

While the saturated hydraulic conductivity of a medium can easily be obtained by the experimental method, the measurement of unsaturated hydraulic conductivity is difficult, costly, and time-consuming. The usage of hydraulic conductivity models is an alternative method of statistically predicting the hydraulic conductivity values of a medium pore size distribution (Burdine, 1953). The findings will provide valuable insights into optimizing the growing medium for improved aeration and moisture management, which are key factors in enhancing crop yield and quality. Understanding the behavior of these mixtures under unsaturated conditions allows for better substrate design, leading to more efficient water use, reduced irrigation frequency, and healthier plants. To deepen the analysis of unsaturated hydraulic conductivity in cocopeat-perlite mixtures, this study employs three well-established hydraulic models: the van Genuchten-Mualem (VGM), van Genuchten-Burdine (VGB), and Brooks and Corey (BC) models. Each of these models is designed to characterize water retention and hydraulic conductivity properties of porous media under unsaturated conditions but differ in their underlying assumptions and mathematical formulations. The VGM model is widely used for its flexibility and ability to describe a broad spectrum of soil types by integrating water retention characteristics with hydraulic conductivity through a continuous function. The VGB model modifies this approach by incorporating a different pore-size distribution function, which can offer a more precise fit for certain substrates. In contrast, the BC model is grounded in a simpler power-law relationship between soil water content and pressure head, making it particularly useful in specific applications where the soil's pore structure is more uniform.

To facilitate the comparison and application of these models, the study utilizes the RETC (Retention Curve) software, a specialized tool designed for estimating the hydraulic properties of soils from water retention data. RETC is widely regarded for its ability to fit these models to experimental data, thereby providing accurate predictions of both saturated and unsaturated hydraulic conductivity (van Genuchten et al., 1991). Thus, the objective of the study was to determine the unsaturated conductivity of the cocopeat-perlite mixture and compare the results using models of VGM, VGB, and BC hydraulic models in RETC software.

2. MATERIALS AND METHODS

2.1. Data collection

This study was conducted with secondary data collected from a study in 2017 by Ilahi (2017), Ilahi and Ahmad (2017) and Ilahi et al. (2017) on the use of different cocopeat-perlite mixtures in the production of butterhead lettuce with a root zone cooling system. Secondary data provides valuable insights over long periods, which is especially useful for comparative analyses. Additionally, using established datasets enhances credibility, as data from reliable sources has often been rigorously validated, increasing the reliability of research findings. The medium mixtures were prepared to six different ratios namely treatments (T); T1 = 100% cocopeat, T2 = 3 cocopeat: 1 perlite, T3 = 2 cocopeat: 1 perlite, T4 = 1 cocopeat: 1 perlite, T5 = 1 cocopeat: 2 perlite and T6 = 1 cocopeat: 3 perlite (Table 1).

A total of ten replications were prepared for each treatment in a completely randomized design. In the study, Ilahi (2017) studied the physical properties of the six different ratios of the cocopeat-perlite mixture including the bulk density, porosity, water retention and saturated hydraulic conductivity of the mixtures. To study the unsaturated hydraulic conductivity of these cocopeat-perlite mixtures, the data on water retention, saturated hydraulic conductivity, and bulk density from Ilahi and Ahmad (2017) and Ilahi (2017) were utilized. Table 2 shows the saturated hydraulic conductivity that has been acquired to predict the unsaturated hydraulic conductivity of the cocopeat-perlite mixtures.

Table 1: Cocopeat-perlite mixture percentage and mixtures ratio.

Treatment	Cocopeat (%)	Perlite (%)	Mixtures Ratio
T1	100	-	-
T2	75.0	25.0	3 cocopeat: 1 perlite
T3	66.7	33.3	2 cocopeat: 1 perlite
T4	50.0	50.0	1 cocopeat: 1 perlite
T5	33.3	66.7	1 cocopeat: 2 perlite
T6	25.0	75.0	1 cocopeat: 3 perlite

Table 2: The saturated hydraulic conductivity of cocopeat-perlite mixture, data are means ± standard error (n=10) (Ilahi, 2017).

Cocopeat-perlite mixture		Saturated Hydraulic Conductivity, ks (cm/s)
100% Cocopeat	(T1)	0.07 ± 0.002d
3 cocopeat: 1 perlite	(T2)	0.09 ± 0.002d
2 cocopeat: 1 perlite	(T3)	0.14 ± 0.012cd
1 cocopeat: 1 perlite	(T4)	0.23 ± 0.008c
1 cocopeat: 2 perlite	(T5)	0.50 ± 0.020b
1 cocopeat: 3 perlite	(T6)	0.97 ± 0.072a

Values in each column with the same letter did not differ significantly at $p<0.05$ according to LSD.

2.2. Hydraulic conductivity models

The data on water retention, saturated hydraulic conductivity, and bulk density of the different mixtures of cocopeat and perlite from the study of Ilahi (2017) were used to predict the unsaturated hydraulic conductivity using three hydraulic conductivity models. The models are VGM, VGB, and BC hydraulic models.

2.3. Brooks and Corey (BC) hydraulic model

The BC model addresses the non-realistic simplifying assumption in the designs of drainage and irrigation systems where soil is assumed to be either completely saturated or completely unsaturated and the resistance to the flow of air is negligible. The function by Brooks and Corey is one of the most widely adopted retention functions in soil water studies (van Genuchten, 1985). It describes the functional relationship between air and water in the medium, the permeability of air and water, and the properties of porous media that affect the relationship. This functional relationship is described in terms of the soil parameters of bubbling pressure and pore size distribution index. The bubbling pressure parameter relates to the continuous flow channels within the medium that form the maximum pore size while pore size distribution index assesses the distribution of sizes of the flow channels in the medium (Brooks & Corey, 1964). The hydraulic conductivity of a medium is described by Brooks and Corey with the equation (van Genuchten, 1980):

$$K\,(h) = (\alpha h) - 2 - 3\lambda \qquad (1)$$

The hydraulic conductivity, K is described as a function of pressure head, h, α is the soil-water characteristic curve setting parameter and λ is the pore-size distribution index.

2.4. van Genuchten – Burdine (VGB) conductivity model

The van Genuchten conductivity model is another hydraulic conductivity model that is popularly used to predict the hydraulic conductivity of the medium. The van Genuchten model derives the medium conductivity based on the water retention curve (WRC) and the conductivity of the medium at saturation (van Genuchten, 1980). The water retention relation is described by the equation (Touma, 2008):

$$S = \left[1 + \left(\frac{h}{h0}\right)\right] - m \qquad (2)$$

Where the degree of effective saturation is represented with S, which is defined with the equation: $S = (\theta - \theta r)/\,(\theta s - \theta r)$, with the parameters of residual water content is θr and θs is the water content during saturation, air entry value *h*0, the curve fitting parameters, m and n (Touma, 2008; van Genuchten, 1980). van Genutchen proposes the closed-form equation to express the hydraulic conductivity of a medium where it is expressed as:

$$K = S2\left[1 - \left(1 - \frac{S1}{m}\right)m\right] \qquad (3)$$

Where K is the value of hydraulic conductivity, S is the effective saturation, and n and m are the fitting parameters that determine the shape of the curve. This equation can be derived under the condition that m = 1-2/n based on Burdine's theory of relative permeability.

2.5. van Genuchten – Mualem (VGM) conductivity model

The VGM model is very popularly used for predicting the hydraulic conductivity (Ippisch et. al., 2006). The model uses the Mualem theory of diffusion and derives a simple integral formula for unsaturated hydraulic conductivity. The theory by Mualem derives the model with the assumption that the length of the interconnected pores is proportional to the radius. Another assumption by Mualem in the theory is the representation of the tortuosity factor and the factor for the partial correlation of pores with a different radius with a power function of the effective saturation at a given water content (Mualem, 1976). Similar to the VGB model, the VGM model has the same parameters, however, the parameter m = 1-1/n is the condition for the equation based on the Mualem diffusion theory (1976). The hydraulic conductivity is expressed as (Touma, 2008):

$$K = \sqrt{S}\left[1 - \left(1 - \frac{S1}{m}\right)m\right]^2 \qquad (4)$$

Where K is the value of hydraulic conductivity, S is the effective saturation and n and m are the fitting parameters that determine the shape of the curve.

2.6. RETC software

The RETC is a software that operates on the Windows operating system created by Šimůnek in 1998. This program can be utilized to estimate the hydraulic conductivity from soil water retention and hydraulic conductivity data at any pressure head. The program also allows the fitting of analytical functions simultaneously to observed water retention and hydraulic conductivity data. The program predicts unsaturated hydraulic conductivity with the theoretical pore-size distribution model from Mualem (1976) and Burdine (1953) and the representation of the soil WRC using the parametric model of Brooks – Corey (1964), Van Genuchten (1980), the log-normal distribution model of Kosugi (1996) and the dual-permeability model of Durner (1994). The RETC is a public domain program that was released and accessible to all online. The system requirements to install the software are an Intel Pentium or higher processor, 16 Mb RAM, hard disk with at least 20 Mb free disk space, VGA graphics (High Color recommended), MS Windows 95, 98, NT, 2000, XP.

Once the program is launched, the main window of the program is opened which leads to the pre-processing settings of units, hydraulic conductivity model, and hydraulic parameters. The graph and data output from the model can be accessed at the post-processing. The hydraulic parameters input includes saturated water content (θs), residual water content (θr), curve fitting parameters of water retention (α and n), and saturated hydraulic conductivity (ks) of the medium. The input parameters set for the hydraulic conductivity model prediction used in RETC are shown in Table 3. These data were extracted from the study by Ilahi (2017) for cocopeat-perlite mixtures.

Table 3: Fitting parameters and coefficient of determination of the van Genuchten (VG) fitted retention curves (Ilahi, 2017).

Cocopeat perlite mixture		θs (m3/m3)	θr (m3/m3)	α	n	ks
100% Cocopeat	(T1)	0.76	0.18	0.05	2.17	0.07
3 cocopeat: 1 perlite	(T2)	0.79	0.24	0.05	2.56	0.09
2 cocopeat: 1 perlite	(T3)	0.81	0.26	0.06	2.45	0.14
1 cocopeat: 1 perlite	(T4)	0.68	0.23	0.14	1.50	0.23
1 cocopeat: 2 perlite	(T5)	0.74	0.26	0.46	1.35	0.50
1 cocopeat: 3 perlite	(T6)	0.61	0.16	1.15	1.20	0.97

3. RESULT AND DISCUSSION

3.1 Unsaturated hydraulic conductivity of different cocopeat-perlite mixture

The values of hydraulic conductivities from three models; VGM, VGB, and the BC model using the RETC program are discussed. Figures 2 to 7 show the output of the predicted hydraulic conductivity values from the RETC program calculated using VGM, VGB, and the BC model. The varying reading of hydraulic conductivity shows the rate of water flow in the medium. A rapid change in hydraulic conductivity as the pressure head decreases shows a fast flow of water flow in the medium.

From Figure 1 to 5, the BC model point does not start at 0 as VGM and VGB model, it is due to the BC model predicts the hydraulic conductivity value at 0 cm H_2O to a value much higher than 1cm/s, the BC line shows a steep line dropping from 0 to -20 cm H_2O. Changes in hydraulic conductivity in T1, T2, and T3 exhibit similar patterns, while the decrease for T1, T2, and T3 are gradual as the pressure head decreases as in Figures 2 to 3. From saturation point at pressure head 0 cm H_2O to -20 cm H_2O, the hydraulic conductivity of T1, T2, and T3 exhibit decreases at a gradual rate, whilst the drop in hydraulic conductivity is slightly higher once the pressure head passes the -20 cm H_2O and becomes more gentle decrease as the pressure head approaches -60 cm H_2O.

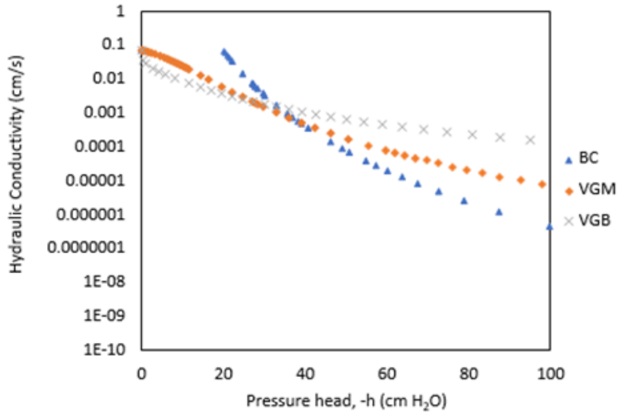

Figure 1: Fitted hydraulic conductivity of T1 = 100% cocopeat for Brooks and Corey (BC), van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

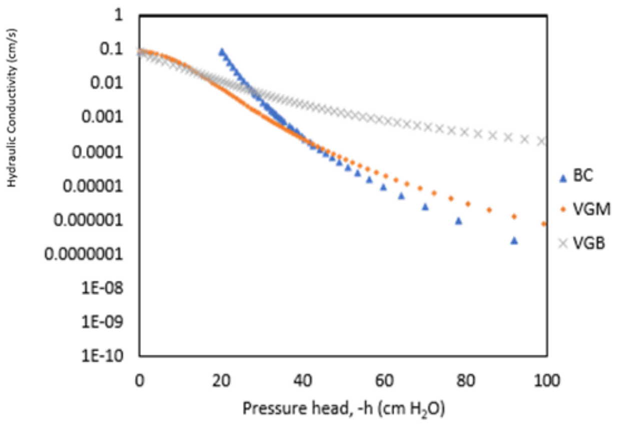

Figure 2: Fitted hydraulic conductivity of T2 = 3 cocopeat: 1 perlite for Brooks and Corey (BC),) van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

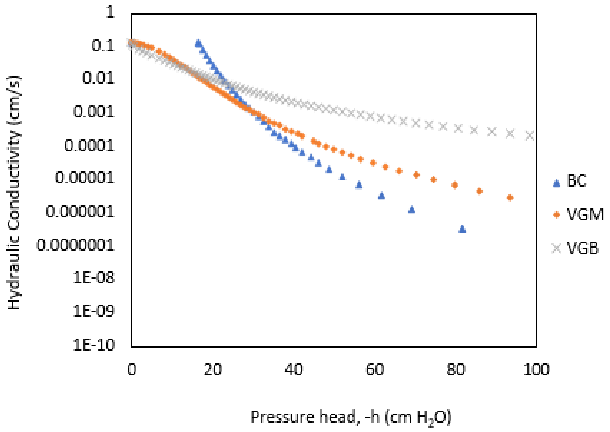

Figure 3: Fitted hydraulic conductivity of T3 = 2 cocopeat: 1 perlite for Brooks and Corey (BC),) van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

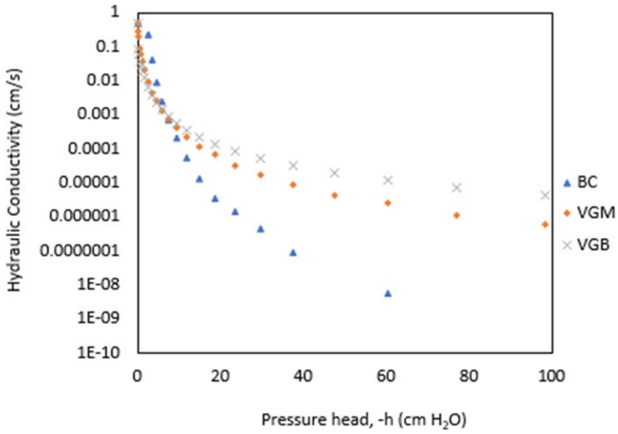

Figure 5: Fitted hydraulic conductivity of T5 = 1 cocopeat: 2 perlite for Brooks and Corey (BC),) van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

Given Figures 4 to 6 display the hydraulic conductivity observed from T4, T5, and T6 which shows the changes in hydraulic conductivity. It can be noticed from the graph, that the hydraulic conductivity falls sharply from the point of saturation to -20 cm H_2O and reduces gently after the pressure head passes through it. However, hydraulic conductivity drops in T5 and T6 are notably larger compared to T4. In summary, the primary differences between the models lie in their starting points and the rate of decline in hydraulic conductivity. The BC model starts from a higher value and drops steeply, while the VGM and VGB models begin at 0 and exhibit a more gradual decline. These differences reflect the varying theoretical approaches to modeling unsaturated hydraulic conductivity and their respective sensitivities to pressure head changes.

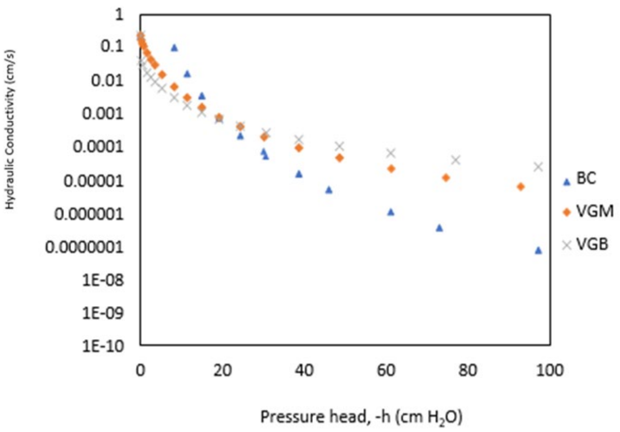

Figure 4: Fitted hydraulic conductivity of T4 = 1 cocopeat: 1 perlite for Brooks and Corey (BC),) van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

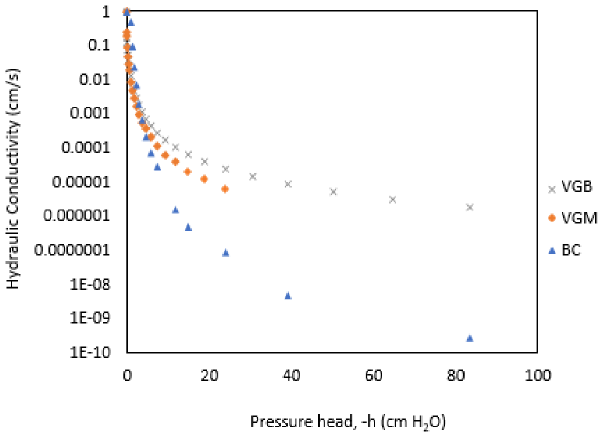

Figure 6: Fitted hydraulic conductivity of T6 = 1 cocopeat: 3 perlite for Brooks and Corey (BC),) van Genuchten – Mualem (VGM) and van Cenutchen – Burdine (VGB) model.

3.2 The water retention curve (WRC) and hydraulic conductivity

The WRC of the six mixtures of cocopeat-perlite depicts the water content in the medium (cocopeat-perlite mixture) at different pressure heads as in Figure 7. This figure was obtained from Ilahi (2017) and refers to air-filled porosity (AFP), easily available water (EAW), and water buffering capacity points as shown. The unit for pressure head kPa in Figure 7 is converted to cm H_2O for easier comparison where 1 kPa is equivalent to -10 cm H_2O.

The water retention of the medium relates to the rate of water flow which can be represented by the hydraulic conductivity values. The high amount of water remaining in the mixtures is shown in WRC reflecting the low rate of hydraulic conductivity. For example, WRC depicted in Figure 7 for T1, water remains stable in the medium pores at -1 cm H_2O to -10cm H_2O. Accordingly, for T1 (control) in Figure 1, at the same range of pressure head, the decrease in hydraulic conductivity is very little for VGM and VGB models. Contrarily with T4, the rapid fall of hydraulic conductivity in Figure 4 for all three models is reflected in the rapid fall of water content in the medium from -1 cm H_2O to -10cm H_2O as observed in Figure 7. At pressure head -80 H_2O to - 100cm H_2O in Figure 7, the decrease in water volume in all mediums seems unchanged as the hydraulic conductivity is also very low. The hydraulic conductivity decreases as the volumetric water content in the medium decreases, the flow of water at the cross-sectional area of the medium is reduced, and tortuosity increases.

The comparison between all treatments shows large decreasing patterns in hydraulic conductivity when perlite medium was added to the mixture. The rate of changes in hydraulic conductivity (K rate) can be arranged from highest to lowest rate; K rate, T6> K rate, T5> K rate, T4> K rate, T3> K rate, T2> K rate, T1. This change rate is much related to the contribution of perlite in the substrate where it contributed to the increment of large pores in the medium thus increasing the water flow rate. A study by Londra (2010) emphasized the relation between water flow in a medium substrate is highly dependent on substrate particle size distribution and pore size. Pressure head 0 to -70 cm H_2O was at rates that are essential for plant development, and it can be observed from T1, T2, and T3 where the plant water uptake is higher. Since cocopeat requires an additive to increase its aeration, the mixture of T2 and T3 can increase its water flow rate without losing too much water due to the porosity increment.

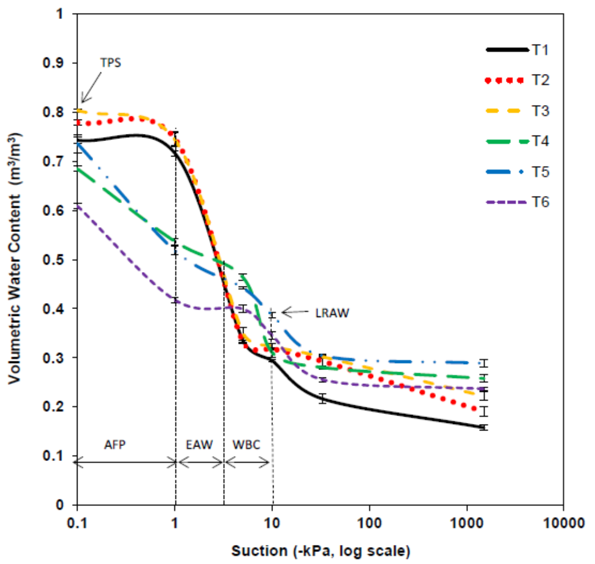

Figure 7: Water retention curve (WRC) for six different cocopeat-perlite mixtures (Source: Ilahi, 2017); Total pore space (TPS), Air filled porosity (AFP), Easily available water (EAW), Water buffering capacity (WBC) and less readily available water (LRAW).

3.3 Hydraulic conductivity models analogy

All models are to be diverged from each other as shown in Figures 1 to 6. At pressure heads 0 cm to 15 cm, results from the VGM model and the VGB model are barely distinguishable, however, passing the 20 cm pressure head, the result of the VGB model is observed to be significantly higher compared to the VGM model and the BC model. The curve divergence is even more pronounced in Figures 3 to 4. A previous study by van Genuchten (1980) points out that the model based on Burdine's theory is less accurate with the experimental result compared to the model based on the Mualem theory and the BC model. However, Touma (2008) proved that both van Genuchten models give fairly accurate results for coarser medium. van Genuchten (1985) reported fewer soils are suited using the Burdine theory especially those that show relatively broad pore size distribution. Anyhow, it may be acceptable to agree with the result obtained from the model due to the nature of the medium.

The hydraulic conductivity by both BC and VGM are fairly close. However, the derivation between both two increases as it closer to saturation. Discontinuity that happened at slopes in T1, T2 and T3 using the BC model near the saturation point was mainly referred to as bubbling pressure was higher when n values were higher than 2 (Brooks and Corey, 1964). Due to this discontinuity, applying the van Genuchten model was preferred to obtain more accurate results when the n value is larger than 2.

The VGM, VGB, and BC models show notable differences in predicting hydraulic conductivity across varying pressure heads. Overall, the VGM model is more reliable for media with broader pore-size distributions, while the BC model is better suited for coarser soils but may show sharp drops near saturation.

4. CONCLUSION

From this study, different hydraulic conductivity models were utilized to estimate the conductivity in six ratios of cocopeat-perlite mixtures. The comparison of the results of the predicted hydraulic conductivity shows that adding perlite into a cocopeat medium will increase the porosity in the substrate which is a requirement to increase aeration for plant roots. However, adding a large amount of perlite may cause the water flow in the medium to be too rapid which would cause water loss which was proven by the results for the cocopeat: perlite ratios of 1:1, 1:2, and 1:3. The mixtures of 3 cocopeat: 1 perlite and 2 cocopeat: 1 perlite shows to have appropriate rate of conductivity change to retain water in the medium still.

Comparing the models used, the VGM and VGB show little difference while the BC model shows a slight discontinuity when the n value for the mixture is higher than 2 due to bubble pressure happening at saturation point near the slopes. Thus, the van Genucthen model was preferable to predict the hydraulic conductivity of the medium.

Understanding the flow of water and water retention in a medium is vital for the irrigation process in soilless culture to ensure good crop performance and reduce water wastage. Future research should explore the hydraulic behavior of these mixtures under varying irrigation regimes and environmental conditions to validate the findings. Additionally, further studies on different substrates or organic additives could enhance the understanding of water dynamics in soilless media. Incorporating more advanced models or testing across a wider range of mixtures may also improve accuracy in predicting hydraulic conductivity for diverse applications in agriculture.

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