Water storage and drainage in perlite in container cultivation

Yuka Hasama\textsuperscript{a}, Yoshiaki Saito\textsuperscript{b} and Jun Ohkubo\textsuperscript{a}

\textsuperscript{a}Graduate School of Science and Engineering, Saitama University, Saitama, Japan; \textsuperscript{b}Interdisciplinary Graduate School of Science and Engineering, Shimane University, Shimane, Japan

\begin{abstract}
The first modelling to predict the moisture content of perlite in container cultivation was performed. In recent years, information technology-based agriculture (smart agriculture), such as automated cultivation of crops, has received considerable attention. One of the important issues in crop cultivation is how to control soil moisture content to achieve optimal conditions for plants. Models that accurately predict the water content in soil are needed. Perlite is often used in containers as a hydroponic soil. Although methods to maintain the moisture content in containers have been studied in the past, there has been no study on how to maintain the moisture content of perlite. In this study, we develop a measurement system, created a model for the water content and drainage of perlite in a container, and analysed the data. The results reveal for the first time a nonlinear trend in the moisture of perlite in containers. The nonlinear model obtained can be used to establish more efficient water supply methods for perlite used in container cultivation.
\end{abstract}

1. Introduction

Recently, the shortage of farmers has become a serious problem in Japanese agriculture. There is considerable interest in the combination of agriculture with information technology (IT), called smart agriculture, as a potential solution to this problem. Image recognition helps in the determination of appropriate treatments, which makes it easier for novice farmers to get started, and automated harvesting of crops using agricultural robots reduces the amount of hard manual labour required. For example, some studies have examined how image recognition can be used to identify diseases from images of leaves [1], while others have determined the centre of swing from images of cherry branches for harvesting [2]. In plant factories and greenhouses, it is easy to control cultivation conditions, and hence several studies have been conducted on how to improve the productivity of crop cultivation in these environments [3]. As an example of improving the efficiency of cultivation in plant factories, the establishment of a closed hydroponic cultivation system for single-stage tomatoes with reuse of wastewater has been reported [4].

Hydroponic targeting of low-potassium melons is an example of greenhouse cultivation [5]. People who are severely restricted in their allowable potassium intake because of reduced kidney function cannot eat conventional melons but can eat low-potassium melons. To cultivate low-potassium melons, advanced cultivation knowledge is needed to strictly control the amount of potassium in the growing medium and hence in the fruit. A sufficient amount of nutrient solution must be provided to the entire container. Although, sufficient nutrient solution distribution throughout the entire container is confirmed by the amount of drainage from the bottom of the container, this approach increases the problem of useless drainage. Although there are some works for the drainage in cultivation, these works cannot be directly applied to the case of the low-potassium melon [6–8].

Additionally, there is an important feature for the cultivation of the low-potassium melon; the low-potassium melons are generally cultivated in containers filled with perlite, which has a porous structure and drains well. Perlite is often used in irrigation systems. Basic research on the cultivation of plants using perlite has been reported [9]. Perlite is also used in carrot and mycorrhizae cultivation [10,11]. However, little research has been conducted on the hydraulic characteristics of perlite in a hydroponic culture in a container. If the moisture behaviour and nutrient content in perlite are estimated and properly controlled, excess drainage can be minimized. Develop equipments for measurement, modelling, and data analysis for planter cultivation with the perlites are important to achieve efficient cultivation of low potassium melons.

In this study, we focused on water storage and drainage of perlite in a container without plants. A measurement system was constructed using a water-supplying motor and soil moisture sensors buried in
several positions in perlite. The water penetration process after water supply at several points in the perlite was investigated, and a model was obtained for estimating drainage. The form of the drainage model reflects the nonlinearity of drainage in perlite. This is the first study to reveal this nonlinear drainage property of perlite. This property could be related to the reduction of drainage.

The remainder of this paper is organized as follows. Section 2 discusses related research. The experiments conducted in this study are described in Section 3. A mathematical model for the drainage process is presented in Section 4, and the measurement results and discussion of the results are provided in Section 5. Section 6 concludes the paper.

2. Related studies

It is useful to understand the behaviour of water in perlite used in containers for irrigation farming, but few studies have directly focused on this. Perlite is a popular soil used in hydroponics, so there could be many benefits to understanding the water behaviour in perlite. Some related trials have been reported. A patent on a container for growing crops presents a design for the shape of the container to maintain good moisture and air conditions for the roots of the crops [12]. Other patents have been issued for container structures for automatic watering of the soil [13]. These patents focus on container structure or design rather than water movement in soil. Of course, some studies have focused on the water state in soil. There is a study on the appropriate timing of watering depending on the characteristics of the plants [14] and a study proposing a sensing system for soil moisture behaviour after watering [15]. However, none of these studies have focused on the water behaviour within the soil. Without understanding water behaviour in soil, it is impossible to maintain good soil conditions for plants and reduce drainage. Understanding water behaviour in soil is necessary to adjust the water supply amount appropriately for the plant’s roots by monitoring the water content. Our research focused on these two considerations. By modelling the water behaviour, it is possible to maintain the amount and timing of water supply at levels suitable for plants while reducing drainage.

Darcy’s equation for water behaviour in saturated soil is well known [16,17]. Because in most cases real soils are unsaturated, there have been attempts to apply this equation to the unsaturated region of real soil [18,19]. These equations may not be solved analytically, so there have been some efforts to predict the moisture behaviour in unsaturated soil by numerical simulation [20]. However, to reduce drainage in container cultivation, it is necessary to grasp the moisture behaviour immediately from sensing and to reflect it in controlling the amount of water supplied in a timely fashion. These are difficult tasks to perform using numerical simulations. Other studies have been conducted to model the water behaviour in unsaturated soil in a laboratory with a controlled soil surface texture. Some of these studies have focused on water infiltration [21] and drying processes [22]. However, the results obtained differ from those obtained in the present study for the following two reasons. The first reason is that these studies examined water behaviour only over a fairly large area. This condition is different from the container cultivation targeted in this study in terms of boundary conditions between soil particles and container surfaces. To model the moisture behaviour in a limited area such as a container, boundary conditions such as changes in moisture movement at the container surface need to be considered. The second reason is that the soils used in these previous studies were beads developed for experimental use in a laboratory, with a controlled particle surface texture and particle size. Perlite is a porous material, and its moisture behaviour is different from that of beads. Therefore, it is necessary to model the moisture behaviour of perlite in containers.

The use of perlite in container cultivation has been studied for the purpose of creating soil with the optimal moisture contents for specific types of plants [23]. There are many benefits to understanding soil moisture behaviour in perlite because it is a commonly used soil in cultivation. The moisture content in perlite has been investigated with the aim of determining a suitable environment for strawberry cultivation [24]. These studies focused on how to make suitable soil for plants in terms of water content, not on the moisture behaviour of perlite in containers. Furthermore, the characteristics of the perlite used in those studies were different from those of the perlite used in the cultivation of low-potassium melons.

3. Experimental setting

3.1. Container setting

We measured the water content of perlite in the same kind of container that is commonly used for low-potassium melon cultivation. Figure 1 is a diagram of
Figure 2. Details of the container, soil moisture sensors, holes, and scales.

Our measurement system, showing the positions of the water supply and drainage. The container used was 100 cm wide, 12 cm high, and 15 cm long. We placed the perlite, which has a porous structure, to a depth of 9 cm from the top of the container, as shown in Figure 2. In the actual cultivation environment, the container is covered by a waterproof sheet, and two holes are drilled in the seeding positions. These holes are 30 cm from the left and right edges of the container and 8 cm in diameter. One of the two holes is for the main measurements and water supply. The other hole is for error analysis, and no water is supplied through this hole. There are six drainage holes in the container. The distance between drainage hole 1 and the left edge of the container is 12.5 cm, and the second drain hole is 15 cm to the right from the first one, and so on. All drainage holes are positioned in the centre in the depth direction. All the drainage hole sizes are 0.8 cm in width and 2.5 cm in depth. We used eight soil humidity sensors (YL-69 and YL-38). Six of them were placed at the centre of the planting area shown in Figure 2. Two of them were placed each 5 cm to the left and right in the main measurement seeding position to study the horizontal infiltration. They were also buried in two layers to study infiltration in gravity direction, one at the soil surface and the other at the centre of soil height.

3.2. Measurement system

An overview of the system for measurement of water storage and drainage is shown in Figure 3. This system can measure air temperature, moisture, luminosity, soil moisture, and drainage. Two Arduino UNO compatibles are used as an analog–digital converter (ADC1, ADC2) for the sensors, except for those for the drainage. Data from sensors connected to the ADCs are transmitted to the measurement PC1 (Raspberry Pi 3B) by serial communication every 2 s, and the measurement PC1 integrates all of the ADC1 and ADC2 measurement data and uploads them to a cloud service.

The two processing units, ADC1 and ADC2, have measurement timing differences because these two processing units have different internal processes. The timing difference can sometimes be several milliseconds. In the analysis stage, a timing flag is introduced to correct the measurement timing difference, and the data are synchronized. ADC2 sets the timing flag for 2 s once every 60 s. ADC1 sends this flag to measurement PC1 in the same way as the measurement data. In the analysis stage, this timing flag is used to correct the ADC1 data to match the processing time of the ADC2 data.

3.3. Water supply system

Periodic water supply to the container is performed at fixed times using a Hanako solar automatic watering device by Funk Trading Co., Ltd. The amount of water supplied to the container is controlled by adjusting the water supply time. This system can supply approximately 50 g of water to the container in 2 s of water supply time. In this experiment, the water supply interval was 15 min, and five water supply time patterns (water supply levels), 1, 2, 3, 4, and 10 s, were used for comparison. There were many water supply time patterns of approximately 2 s because the time interval of 2 s is generally used for low-potassium melon cultivation. For comparison, a level of 10 s was also measured.

3.4. Measurement system for drained water

There are six drainage holes at the bottom of the container, as shown in Figures 1 and 2. Cups for receiving drainage from each drainage hole were set below, and the amount of drainage from each drainage hole was measured in 0.1-g units using mass meters. The measured value displayed on each mass meter was photographed every 1 s using a web camera, and the amount of drainage was determined from these photographed measurements. The timing of the drainage measurement was controlled by PC2, and other sensors were monitored by PC1, as described above. To synchronize the measurement timings of these two PCs, the deviation of the internal times between the PCs was adjusted to be less than 1 s.

4. Model

4.1. Soil moisture model

For the soil moisture sensor value $y$, a phenomenological model was fitted to the measured data. The timing
of the water supply was set to \( t = 0 \), with the positive direction representing the dryness. The following equation form was used:

\[
y(t) = d_0 + d_1 \cdot \exp\left(-\frac{t}{T_1}\right) - d_2 \cdot \exp\left(-\frac{t}{T_2}\right),
\]

(1)

where \( d_0 \) is the water content in the steady state, \( d_1 \) and \( d_2 \) are the water contents at the time of water supply, and \( T_1 \) and \( T_2 \) are time constants representing the water penetration. The first term is the process in which water content increases immediately after the water supply (hereinafter referred to as the “water supply process”) and the other is the process in which water permeates into the surrounding soil after the water supply (hereinafter referred to as the “infiltration process”). The second and third terms in Equation (1) are the water supply process and infiltration process, respectively.

### 4.2. Drainage model

A model for water drainage in perlite soil, especially for the case of pulsed water supply such as in our water supply system, is discussed in this section. At first, the perlite is dry, and there is no drainage when a small amount of water is supplied. When large, pulsed water is supplied to the system, periodic drainage will occur (the drainage process) after the water infiltrates the soil (the infiltration process). This section presents a modelling method for the drainage process after most of the supplied water is expected to be drained, which means that the soil is so wet that infiltration does not occur.

The amount of water supplied at once is defined as the hydraulic height \( h_{\text{in}} \), which is the height of water in a container with a bottom area \( A \). The amount of drainage \( D_{dk} \) at the drainage hole \( dk \) is represented by the following equation:

\[
D_{dk}(h_{\text{in}}, n) = (v_{dk} + \gamma) \cdot n + \beta \\
= (\alpha_{dk} \cdot h_{\text{in}} + \gamma) \cdot n + \beta,
\]

(2)

where \( n \) is the water supply count, \( v_{dk} \) is the drainage volume per one-time water supply, \( \alpha_{dk} \) is the area divided by the drainage, and \( \beta \) and \( \gamma \) are adjustment constants. To obtain a more accurate prediction of \( D_{dk} \), we consider the temporal change in drainage, which is affected by the amount of water supply at one time. For this purpose, we adopted a simplified model based on Darcy’s law [16,17]. As shown in Figure 4, the following initial situation is assumed: the soil has an area \( A \) and a height \( L \), and the supplied water has height \( h \) uniformly contacted on the upper surface of the soil. Water permeates and drains through a sufficiently wet soil. We assumed that water had permeated into the sufficiently moist soil over time and shifted to the drainage process. The amount of drainage is equal to the amount of water supplied to the soil because it is sufficiently moist. We discuss the case in which a change in \(-\Delta h\) occurred at \( \Delta t \) after the initial state. It is assumed that water moves through the soil at a constant speed \( v \). According to Darcy’s law [16,17], the relationship between the water flow speed \( v \) and height \( h \) is given by the following equation:

\[
v = \frac{k}{L} h,
\]

(3)

where \( k \) is a constant. The water volume \( \Delta V \) moved during \( \Delta t \) is as follows:

\[
\Delta V = Q\Delta t = vA\Delta t = -A\Delta h
\]

(4)

where \( Q \) is the volume flow rate. The following equation is derived from Equation (3):

\[
Q\Delta t = vA\Delta t = \frac{k}{L} A\Delta t
\]

(5)

Then, Equations (4) and (5) lead to

\[
-\frac{k}{L} \Delta t = \frac{\Delta h}{h}
\]

(6)

Time integration with \( h_{\text{in}} \) as the initial constant yields the following:

\[
h = h_{\text{in}} \cdot \exp\left(-\frac{t}{\tau}\right)
\]

(7)

\[
\tau = \frac{L}{k}
\]

(8)

In the analysis described in Section 5, the time constant \( \tau \) was found to play an important role. The velocity of the drainage is derived from Equations (3) and (7), as follows:

\[
v(t) = \frac{h_{\text{in}}}{\tau} \cdot \exp\left(-\frac{t}{\tau}\right)
\]

(9)

and the amount of drainage \( D \) was obtained from Equation (9), as follows:

\[
D = \int_0^t A \cdot v(t) \, dt = A \cdot h_{\text{in}} \left[1 - \exp\left(-\frac{t}{\tau}\right)\right]
\]

(10)

If the time span from one water supply to the next water supply is sufficiently long, \( D \) becomes \( D = A \cdot h_{\text{in}} \), which is the same as Equation (2).
5. Results and discussion

5.1. Soil moisture sensor

A comparison between the measured data and the water content model is shown in Figure 5. The water content model reflects the same behaviour as the measured data.

The parameters for applying the water content model to the measured data are shown in Table 1. They are found by fitting Equation (1) to every 14 times measured data using the least-square method. Every parameters $d_1$, $d_2$, $T_1$, $T_2$ are mean values of the total 14 times measurement. Parameters $d_1$ and $T_1$ indicate sharp water content increase states after the water supply, and $d_2$ and $T_2$ indicate water infiltration states into the surrounding soil after the water content increase.

Soil moisture sensors were positioned at the centre of the soil surface (high centre), on the left and right sides of the soil surface (high left and high right), and at the centre of the deep layer of soil (low centre). The soil humidity value used is the average of all the data from these sensors.

The coefficient of determination ($R^2$) is low for all of the data combined. For the centre of the soil surface and the left and right sides of the soil surface, the amount of data obtained was small, and the sensor accuracy was poor. The coefficient of determination was lower for the left and right soil surfaces than for the centre of the soil surface. The soil humidity at the centre of the soil surface fluctuated greatly at the time of water supply, but the soil humidity at the left and right sides of the soil surface fluctuated less. Therefore, the accuracy of the data was considered to be worse at these latter locations. The coefficient of determination was lowest at the deep centre point in the soil. This is because the time lag for water to move from the surface to the deeper layers is not taken into account. Improvement of the water content model was required to improve the coefficient of determination at the deep centre point. However, as Figure 5 shows, we can confirm that the model fits the measured data well, and hence there is no problem for the analysis here.

We analysed the water content of the soil based on the parameter values shown in Table 1. The value of $T_2$ is almost constant, and the process of moisture infiltration to the surrounding area is not related to the location of the soil. The reason that $T_1$ was fixed at 1.0 is that the measurement period was 2 s, which is too long to observe water infiltration by water supply.

The peak values, which represent the amount of moisture, were calculated from $d_1$, $d_2$, $T_1$, and $T_2$. The values were $-7.91$, $-2.15$, $-2.13$, and $-3.24$ for the centre of the soil surface and the left, right, and deep centre locations, respectively. The larger value for the centre of the deep layer than those for the left and right sides of the soil surface indicates that the water supplied to the soil flow downward to a greater extent than it flowed to the left and right.

5.2. Drainage

Figure 6 shows the measured data of soil moisture sensors and the drainage at the 3-s level (water supply level). The soil moisture sensor data measurements showed sharp increases at the water supply times and gradual increases over time. The reason that data at the low centre is almost constant is too much soil moisture to detect. Because left water injected in previous measurements was collected around this sensor, it became constant even after water supplements start. In this paper, we ignored data before constant, which is expected to be influenced by previous measurements. After the start of the experiment, no drainage occurred for a short time because the infiltration process takes priority over the drainage process. In this study, we

![Figure 5](https://example.com/fig5.png)  
**Figure 5.** Water content model and measured values. The “measured” data is the one for the final timing at the “high centre” position. The “model” curve is the fitted result.

| Parameter | High centre | High left | High right | Low centre |
|-----------|-------------|-----------|------------|------------|
| $d_1$     | 15.4        | 4.58      | 4.57       | 6.82       |
| $d_2$     | 14.9        | 4.13      | 4.09       | 6.19       |
| $T_1$     | 1.0         | 1.0       | 1.0        | 1.0        |
| $T_2$     | 5.007       | 5.000     | 5.001      | 5.008      |
| $R^2$     | 0.78        | 0.57      | 0.59       | 0.45       |

![Figure 6](https://example.com/fig6.png)  
**Figure 6.** Measured sensor data for soil moisture (upper), and drainage (lower).
investigated the drainage process, which has an almost constant contribution and is equal to the water supply.

The drainage was modelled using Equation (2), and the results are shown in Figure 7. The horizontal axis indicates the water supply \( h_{in} \), and the vertical axis indicates the drainage volume \( v_{dk} \). The results of the fitting are shown in Figure 7. We defined one water supply as a supplied water after the start of a water supply. Especially, Figure 7 shows of one-time water supply at from 2 h to 2 h 15 min. The data, except those for drainage holes 2 and 3, did not show periodic drainage because the amount of drainage was less than the lower limit of the mass meter. Therefore, the drainage at the end of measurement was divided by the measurement time, and the values were plotted as shown in Figure 7. Each \( R^2 \) is close to 1, and each relation can be approximated by a straight line.

The value of \( \alpha_{dk} \) tends to be large as the drainage hole gets close to the water supply point, and hence, \( \alpha_2 \) and \( \alpha_3 \) have larger values than \( \alpha_1 \) and \( \alpha_4 \). However, \( \alpha_3 \) is larger than \( \alpha_2 \) even though drainage hole 3 was slightly farther from the water supply point than the drainage hole 2. We consider this may be because of the well drainage characteristics of perlite.

5.3. Time constant

The drainage characteristic of one water supply is represented by a time constant \( \tau \). The hydraulic conductivity, which is expected to represent the properties of the soil, is also represented by \( \tau \). Hence, if the change in \( \tau \) is known, the moisture condition in the soil can be estimated. When the flow of water is one-dimensional and has no directionality, the drainage per water supply can be expressed by Equation (10) according to Darcy’s law.

Figure 8 shows \( \tau \) at drainage hole 2 and hole 3. The error bars show the standard errors estimated from 12 measurements, except for the 10 s of water supply level. At the 10 s water supply level, data only for three measurements was analysed because the amount of data was small due to a large amount of water drainage at one time. In some analyses, we employed outlier treatment. According to Equation (8), \( \tau \) does not depend on the water supply amount \( h_{in} \). However, \( \tau \) at hole 3 decreases notably as the water supply increases. Additionally, there is a relatively sharp change in \( \tau \) when the water supply level is between approximately 2 s and 3 s. When the water supply amount is small, the water permeates the perlite particles, and hence the water flow speed does not change again. The nonlinearity, i.e. the rapid change of \( \tau \) in the middle region in Figure 8, indicates that air and moisture coexist in the perlite and that the superior drainage effectiveness of the perlite produces the sudden change.

We believe that awareness of this nonlinearity will be useful in control of soil moisture for plants and in optimizing plant growth. For example, an oversupply of water causes root rot in plants. On the other hand, low soil moisture causes plants to wither. Therefore, an appropriate ratio of soil moisture to air is important for plant growth. However, it is not clear how the variations in the water supply position and drainage position affect the nonlinearity. In the future, we will analyse and model the nonlinearity of \( \tau \) because we would like to estimate the soil moisture over a wide area using a few soil moisture sensor points. We believe that our research on the nonlinearity of soil moisture will contribute to agricultural development.

6. Conclusions

In this study, we revealed the nonlinear characteristics of the water content of perlite in containers for the first time. We created an automatic water supply system for containers using a type of perlite used as porous soil in hydroponics. Use of soil humidity measurements obtained with a sensor installed in the container results in a phenomenological model with improved precision. Using measurements of drainage from the holes under the container, we modelled the drainage in a linear form in terms of the amount of water supply and the number of times that water was supplied.

Additionally, the change in the amount of drainage over time for a single application of water was studied. The value of the observed time parameter \( \tau \) was not constant, as would be expected from Darcy’s law, but rather exhibited nonlinearity with respect to the water supply amount. As more water was supplied, the value...
of the time parameter gradually decreased, but a sudden drop was found to occur at a specific water supply value. The water content might change rapidly because perlite has a well-water-drain feature. In the future, we will analyse and model perlite drainage using soil moisture sensors and considering the effects of the infiltration process, position, and distance to determine how to maintain an appropriate water content in perlite. Our current measurement and analysis methods suggest that the water content in perlite can be accurately predicted and controlled. Hence, it should be possible to maintain the optimal moisture environment automatically for plants grown in perlite in containers, which need a balance between air and water for optimal growth.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Yuka Hasama (Student Member) She received the BSc and MSc degree from Tokyo Institute of Technology in 2008 and 2010, respectively. She had worked Toyota Technical Development Corporation since 2010 to 2012. She currently joined Komatsu Ltd. and is a doctoral student of Saitama university.

Yoshiaki Saito (Member) He received the B E and ME degree in electrical engineering from Hosei University in 1999 and 2001. He joined Komatsu Ltd. in 2001. He is currently a doctoral student of Shimane University. His research theme in university is body recognition in virtual space.

Jun Ohkubo (Member) He received the PhD degree from Tohoku University in 2007. In 2007, he joined the Institute for Solid State Physics, the University of Tokyo, as an Assistant Professor. He was a Lecturer with the Graduate School of Informatics, Kyoto University from 2010 to 2015. He is currently an Associate Professor with the Graduate School of Science and Engineering, Saitama University. His research interests include applications of stochastic processes, probabilistic information processing, and machine learning.

References

[1] Sladojevic, S, Arsenovic M, Anderla A, et al. Deep neural networks based recognition of plant diseases by leaf image classification. Comput Intell Neurosci. 2016;2016, Art. no. 3289801.

[2] Amatya S, Karkee M, Zhang Q, et al. Automated detection of branch shaking locations for robotic cherry harvesting by using machine vision. Robotics. 31, 2017;6(4), Art. no. 31.

[3] Morimoto T, Torii T, Hashimoto Y. Optimal control of physiological process of plants in a green plant factory. Control Eng Pract. 1995;3(4):505–511.

[4] Okano K, Sakamoto Y, Watanabe S, et al. Establishment of a closed hydroponic system in single-truss tomato by the reuse of concentrated drainage. Environ Control Biol. 1999;37(1):63–71.

[5] Asao T, Asaduzzaman M, Mondal MF, et al. Impact of reduced potassium nitrate concentrations in nutrient solution on the growth yield and fruit quality of melon in hydroponics. Sci Hortic. 2013;164(17):221–231.

[6] Beeson RC, Arnold MA, Bilderback TE, et al. Strategic vision of container nursery irrigation in the next ten years. J Environ Hortic. 2004;22(2):113–115.

[7] Majsztrik JC, Fernandez RT, Fisher PR, et al. Water use and treatment in container-grown specialty crop production: a review. Water Air Soil Pollut. 2017;228, Art. no. 151.

[8] Wei Y, Cejas CM, Barrois R, et al. Morphology of rain water channeling in systematically varied model sandy soils. Phys Rev Appl. 2014;2(4), Art. no. 044004.

[9] Eltrop L, Marschner H. Growth and mineral nutrition of non-mycorrhizal and mycorrhizal Norway spruce (Picea abies) seedlings grown in semi-hydroponic sand culture. New Physiol. 1996;133(3):469–478.

[10] Kumari S, Pradhan P, Yadav R, et al. Hydroponic techniques: a soilless cultivation in agriculture. J Pharmcogn Phytochem. 2018;7(15):1886–1891.

[11] Colpaert JV, Van Tichelen KK, Van assche JA, et al. Short-term phosphorus uptake rates in mycorrhizal and non-mycorrhizal roots of intact Pinus sylvestris seedlings. New Physiol. 1999;143(3):589–597.

[12] Staby GL. Container with raised indentations for aeration and drainage. US patent, 4173097. 1979.

[13] Lee JC. Planter assembly having automatic watering and feeding intervals. US patent, 5502924. 1996.

[14] Mathers HM, Yeager TH, Case L. Improving irrigation water use in container nurseries. Hort Technol. 2005;15(1):8–12.

[15] Zhu H, Krause CR, Zondag RH, et al. A new system to monitor water and nutrient use in pot-inpot nursery production systems. J Environ Hortic. 2005;23(1):47–53.

[16] Darcy H. Les fontaines publiques de la ville de Dijon, Dalmont, 1856. 1970.

[17] Verruijt A. Theory of groundwater flow, p.6–13, Macmillan Education UK, 1970.

[18] Richards AL. Capillary conduction of liquids through porous media. Physics. 1931;1(5):318–333.

[19] Bruce RR, Klute A. The measurement of soil moisture diffusivity. Soil Sci Soc Am J. 1956;20(4):458–462.

[20] Carsel RF, Parrish RS. Developing joint probability distributions of soil water retention characteristics. Water Resour Res. 1988;24(9):755–769.

[21] Cejas CM, Castaing J-C, Hough L, et al. Experimental investigation of water distribution in a two-phase zone during gravity-dominated evaporation. Phys Rev E. 2017;96(6), Art. no. 062908.

[22] Faure P, Coussot P. Drying of a model soil. Phys Rev E. 2010;82(3), Art. no. 036303.

[23] Magwaza MT, Magwaza LS, Odindo AO, et al. Hydroponic technology as decentralised system for domestic wastewater treatment and vegetable production in urban agriculture: a review. Sci Total Environ. 2020;698, Art. no. 134154.

[24] Ors S, Anapali O. Effect of soil addition on physical properties of perlite based media and strawberry cv. Camarosa plant growth. Sci Res Essays. 2010;5(22):3430–3433.