Predicting the Temperature and Moisture of Soil in Cylindrical Containers used for Planting with 3D model

Wirote Kruapoo[1], Worasitti Sriboon[2], and Usavadee Tuntiwaranuruk[1]*

[1]Department of Physics, Faculty of Science, Burapha University, Chon Buri, 20131, Thailand.
[2]Department of Basic Science and Physical Education, Faculty of Science at Si Racha, Kasetsart University Si Racha Campus, Chon Buri, 20230, Thailand.

*Corresponding author. E-mail: usavadee@buu.ac.th

ABSTRACT

This research aimed to predict the temperature and moisture of soil in cylindrical containers used for planting by using cylindrical mathematical 3D model based on the theory of heat and mass transfer, and then compare them with those resulted from the experiment in the container with 80 cm in diameter and 40 cm in height. The study revealed little difference in soil temperature and moisture as measured by 3D model and by the experiment. The temperature predicted by the 3D model was found to be in relation to that measured from the experiment in all depths (10, 20, 30, 40 cm). The statistical analysis revealed Coefficient of Determiner (R^2) closer to 1, and a minimum of Mean Absolute Percentage Error (MAPE). Therefore, the created 3 D model was found to be reliable in predicting soil temperature and moisture in the cylindrical containers, which could be used as basic information for choosing the kinds of plants suitable for growing in such containers, and for predicting temperature, and moisture—two essential factors for plant growth.

Keywords: soil temperature, soil moisture, mathematical model, containers, plant growth

INTRODUCTION

It is well accepted that soil temperature and moisture are inter-related and are essential for plant growth (Kunkel et al., 2016; Tenge et al., 1998), and also influence various processes within the soil. A number of experiments have been conducted and mathematical models have been developed to predict soil temperature and moisture (Kunkel, Wells, and Hancock, 2016; Díaz-Pérez, 2009). However, those experiments were conducted on soil in their natural setting. The study of soil in planting containers have been very limited (Sriboon et al., 2017). Planting in containers, particularly in concrete septic tanks, of lime trees and kaffir lime trees for domestic consumption and for commercial purpose has become popular due to their availability, low cost, and suitability for varieties of plants. The prediction data of soil temperature and moisture can be used for selecting the appropriate plants to grow in the planting containers. This method is fast, convenient, cost reduction for equipment, and time saving for collecting data (Banimahd and Zand-Parsa, 2013).

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This research aimed to build a 3D mathematical model for predicting soil temperatures and moistures in cylindrical concrete containers. The model was validated by using statistical analysis which was then compared to the data from soil temperature and moisture measurements from the experiment field. The result would be used as information support to decide which plants are suitable for planting in cylindrical concrete containers.

THEORY AND METHODS

Heat and Mass Transfer Equations in Soil

The equation on energy in multi-component system, a result of heat, mass, and momentum transfer, with the exclusion of earth gravity, conforming to conservation law, is the following: (Bird et. al., 2005):

$$\rho C_p \frac{DT}{Dt} = -(\nabla \cdot \mathbf{q}) - (\boldsymbol{\tau}:\nabla \mathbf{v}) + \left(\frac{\partial \ln \hat{V}}{\partial \ln T}\right)_{p,x_i} \frac{Dp}{Dt} + \sum_{i=1}^{n} \overline{H}_i [(\nabla \cdot \mathbf{J_i}) - R_i] \quad (1)$$

where ρ is the whole density (kg/m^3), C_p is specific heat capacity (kJ/kg-$^\circ$C), T is temperature ($^\circ$C), t is time (s), $\mathbf{q}$ is heat transfer flux (W/m^2), τ is shear stress (kg/m-s^2), $\mathbf{v}$ is velocity (m/s), $\hat{V}$ is specific volume (m^3/kg), p is pressure (kg/m-s^2), $\overline{H}_i$ is molar enthalpy (J/mole), J_i is molecular flux (mole/s-m^2), and R_i is molecular reaction rate (mole/s-m^3). The second and third terms on the right hand side of equation (1) can be neglected in this study due to the assumption that the fluid diffusion is too small to affect viscous dissipation, and due to the small change in the volume and pressure in the system.

Heat transfer in soil is mainly dominated by thermal conduction (Hillel, 2003). The steady-state heat transfer in cylindrical containers can be written as the following:

$$q_{CD} = \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \emptyset}\left(kr\frac{\partial T}{\partial \emptyset}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \quad (2)$$

where k is the thermal conductivity (W/m-K), r is radial coordinate, ϕ is azimuth angle, and z is the vertical coordinate.

For the last term on the right in the equation (1), The R_i term can also be considered as none due to the absent of chemical reaction. Therefore, the energy transfer from mass flux with multi-components and diffusion will be considered as $\mathrm{J_i}$ which is a result from Fick's law of diffusion, and can be expressed as the following equation (Bird et al., 2005):

$$\mathbf{J} = -\rho \mathrm{D_m}(\boldsymbol{\nabla} \cdot \omega) \tag{3}$$

where $\mathbf{J}$ is mass flux (kg/s-m^2), ρ is density (kg/m^3), and $\mathrm{D_m}$ is moisture diffusion coefficient. The moisture diffusion coefficient can be obtained by using the relation $\mathrm{D_m} = 0.66\, f_a\, D_o$ (Penman, 1940), where f_a is air-filled porosity (m^3/m^3), $\mathrm{D_o}$ is vapor diffusion coefficient in free-air (m^2/s) (Xu et al., 1992; Allaire et al., 2008), and ω is soil moisture ratio (%). Therefore, by combining equation (1) to (3), one can write as following:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{\mathrm{k}}{\rho \mathrm{c_P}} \nabla^2 \mathrm{T} - \frac{\mathrm{H}}{\mathrm{c_P}} \frac{\partial \omega}{\partial \mathrm{t}} \tag{4}$$

Energy Balance and Soil Surface Mass

When solar radiation reaches the earth surface, some amount of energy was absorbed and transfer down deep into the soil, thus increase the soil temperature, and some of it goes to surrounding environment. The energy balance on the soil surface at thermal equilibrium can be expressed as following:

$$\mathrm{q_{SL}} = \mathrm{q_{CD}} + \mathrm{q_{CV}} + \mathrm{q_{RD}} + \mathrm{q_{MD}} \tag{5}$$

where $\mathrm{q_{SL}}$ is thermal energy from solar radiation incident on soil surface (W/m^2), $\mathrm{q_{CD}}$ is the conduction heat transfer into the soil (W/m^2), $\mathrm{q_{CV}}$ is convection heat transfer at soil surface (W/m^2), $\mathrm{q_{RD}}$ is net radiation heat transfer between soil surface and sky (W/m^2), and $\mathrm{q_{MD}}$ is the energy due to water evaporation as shown in Figure 1.

The thermal energy absorbed from incident solar radiation can achieved from:

$$\mathrm{q_{SL}} = \alpha \mathrm{I} \tag{6}$$

where I is solar irradiance on soil surface (W/m^2), α is solar absorptance. Collares-Pereira and Rabl (1979) has proposed the correlations to determine hourly total radiation from the daily total radiation (Tiwari, 2013):

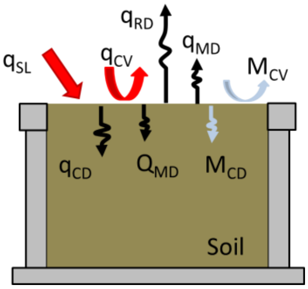


Figure 1: Energy Balance and Mass at Soil Surface

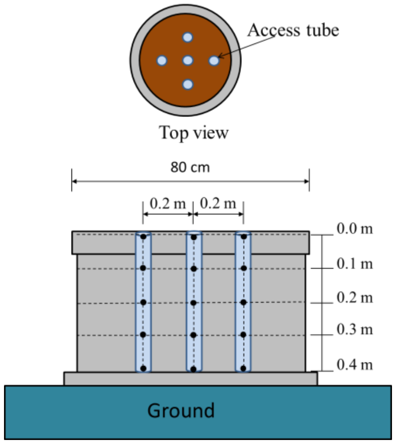


Figure 2: Measuring Tool Installment

$$I(t) = r_t \bar{H}_o/3600 \tag{7.1}$$

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - (2\pi\omega_s/360)\cos\omega_s} \tag{7.2}$$

where $\bar{H}_o$ is monthly average of daily extraterrestrial radiation on horizontal surface (MJ/m^2-day), The coefficient a and b are given by; $a = 0.409 + 0.5016\sin(\omega_s - 60)$, $b = 0.6609 - 0.4767\sin(\omega_s - 60)$, ω is hour angle (degree), and ω_s is sunset hour angle. The convection heat transfer can be expressed as following:

$$q_{CV} = \bar{h}_c(T_s - T_\infty) \tag{8}$$

where $\bar{h}_c$ is mean convection heat transfer coefficient (W/m^2-K), T_s is soil surface temperature (K), and T_∞ is air temperature (K). The convection heat transfer coefficient from the wind at soil surface depends on wind speed. The correlation for convection coefficient can be written as $h_c = 5.7 + 3.8$ V, which V is wind speed (m/s) (Tiwari, 2013). The net radiation to the soil surface (q_{RD}) is shown as following:

$$q_{RD} = \sigma\varepsilon\left(T_s^4 - T_{sky}^4\right) \tag{9}$$

where σ is Stephan-Boltzmann's constant = 5.67 x 10^{-8} (W/m^2-K^4), ε is emittance, and T_{sky} is sky temperature which is determined from relation: $T_{sky} = 0.0552T_{amb}^{1.5}$. The energy associated with water evaporation at soil surface (q_{MD}) is described by (Klompong, 2008):

$$q_{MD} = F(u)\left(b\,(1 - RH) - a\,(RH \times T_{amb} - T_s)\right) \tag{10}$$

where RH is relative humidity (%) in the temperature range: $263 \leq T \leq 303$ K, the coefficient a and b are given as: a = 103 Pa/K, and b = 609 Pa, and the relationship $F(u) = -0.0168\, f\, h_c$, the value of f will be 1 for saturated soil, 0.6-0.8 for wet soil, 0.4-0.5 for dry soil, and 0.1-0.2 for very dry soil. The soil surface is losing its moisture to the atmosphere due to the convection, and also the water diffusion due to the moisture gradient in the soil layers. Then, the mass balance at soil surface can be considered as:

$$M_{CV} = M_{CD} \tag{11}$$

where M_{CV} is mass transfer of moisture due to convection (kg/s), and M_{CD} is mass transfer in soil layers (kg/s). Convective mass transfer can be expressed by the following equation:

$$M_{CV} = h_m A \left(\rho_{v,s} - \rho_{v,\infty}\right) \tag{12}$$

where h_m is mass transfer coefficient (m/s), A is area (m^2), $\rho_{v,s}$ is water vapor density at soil surface (kg/m^3), $\rho_{v,\infty}$ is water vapor density in the ambient air (kg/m^3).

Equipment Installment and Measurement

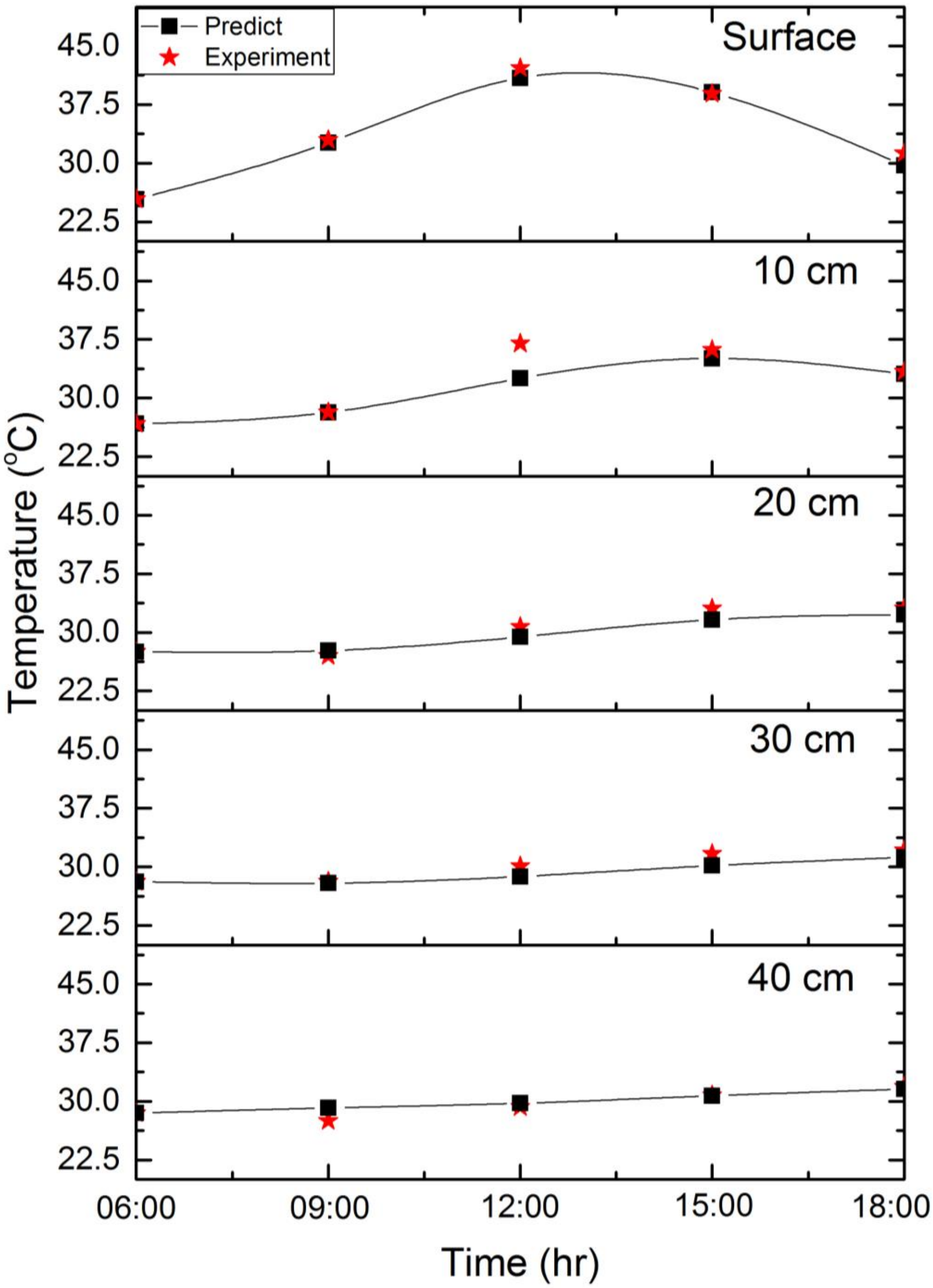
The experiment was conducted in a lime orchard in Si Racha, Chon Buri, Thailand. The temperature and moisture of the soil in concrete cylindrical containers with a diameter of 80 cm and 40 cm in height were recorded. Sensor probes were installed at 20 different positions within the containers. Figure 2 shows the 5 different depths of the measurement which are 0, 10, 20, 30, and 40 cm from the soil surface. Each layer consists of 4 probes located at radius of 20 cm from the center and placed at northern, southern, eastern, and western direction with respect to the experimental site. Soil temperatures were measured with thermocouple type K and collected by data logger machine model BTM-4208 SD. Data of surroundings, such as ambient temperature, relative humidity, wind speed and direction were measured and recorded hourly by meteorological instrument. Soil temperature and moisture were recorded every 3 hours starting from 6:00 am to 6:00 am of the next day, with the total of 24 hours.

Results and discussions

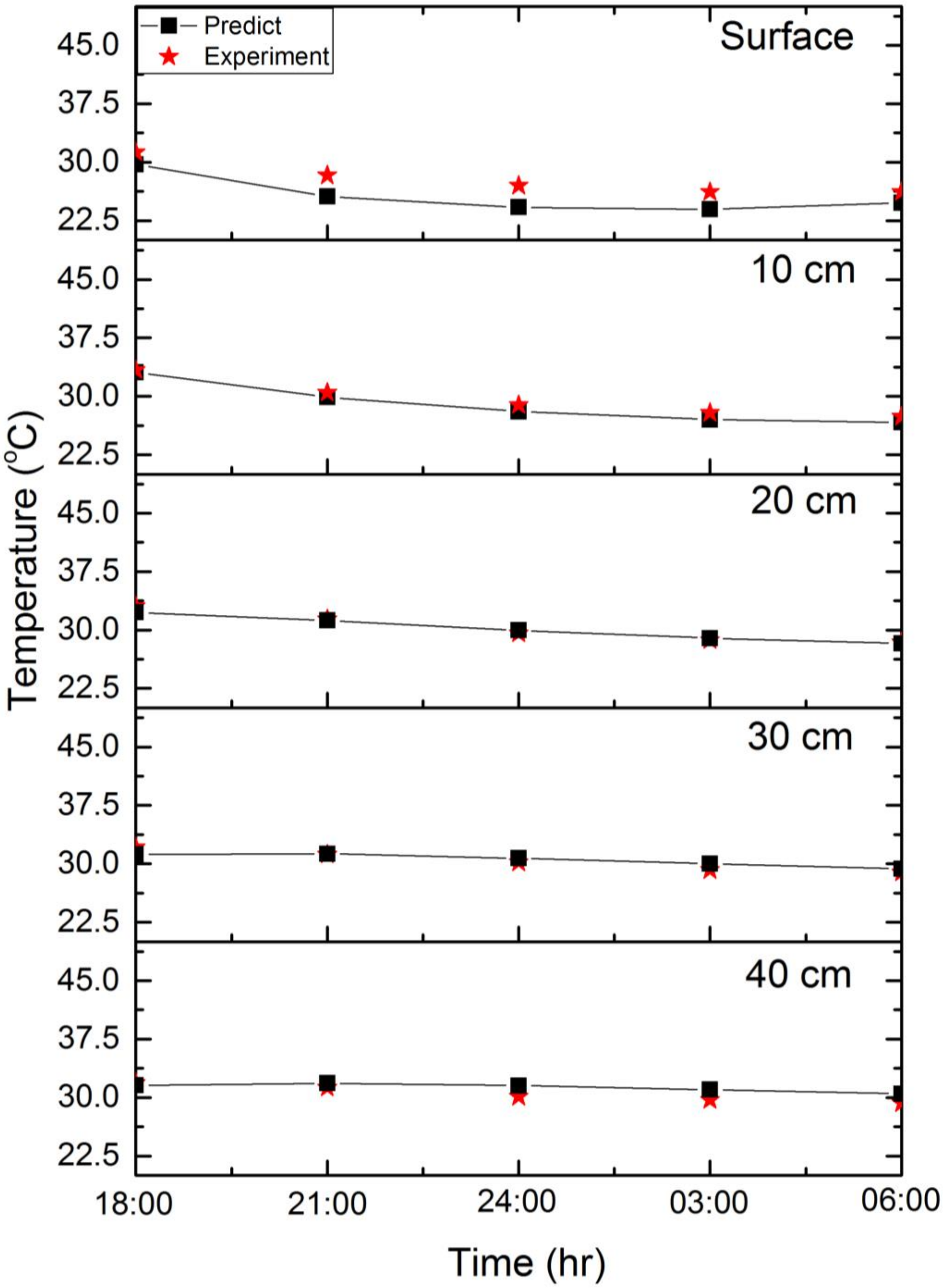
Figure 3 and Figure 4 show the soil temperature and moisture, respectively, in the concrete container from the experiment and model. The model was constructed to predict soil temperature and moisture using the same geometry with the concrete container. The statistical devices used for data analysis were the Coefficient of Determination: R^2 and the Mean Absolute Percentage Error: MAPE. The measurement was conducted during daytime (from 6:00 am to 6:00 pm), and nighttime (6:00 pm to 6:00 am).

Figure 3(a) and 3(b) show the soil temperature during daytime and nighttime which predicted by mathematical model and measured from experiment. It shows that the temperature changes in the same trend and shows a good agreement between model and experiment data. The R^2 at the depths of 0, 10, 20, 30, and 40 cm during daytime were found to be 0.9859, 0.8643, 0.9606, 0.9185 and 0.8563 respectively, and 0.9355, 0.9990, 0.9701, 0.8582, 0.6440 during nighttime respectively. The values of R^2 is close to 1 which means the model represents a good fit, statistically. The MAPE at the depths of 0, 10, 20, 30 and 40 cm during daytime were also found to be very low of 0.0194, 0.0325, 0.0268, 0.0254 and 0.0178, respectively, and 0.0783, 0.0234, 0.0111, 0.0180 and 0.0321 during nighttime.

Figure 4(a) and 4(b) show the soil moisture during daytime and nighttime which predicted by mathematical model and measured from experiment. It also shows that the moisture changes in the same trend. The R^2 at the depths of 0, 10, 20, 30, and 40 cm during daytime were found to be 0.7836, 0.4722, 0.5455, 0.7646 and N/A, respectively, and during nighttime of 0.3594, 0.4747, 0.5344, 0.1163 and 0.4793, respectively. The values of R^2 are considered low especially during nighttime. One reason is that the assumption about moisture transfer of this model based on only diffusion mechanism which is not suitable for liquid water but gaseous phase. However, the MAPE was found to be 0.0045 - 0.1120 during daytime and 0.0187 - 0.1571 during nighttime, showing similar soil moisture measured by both means.

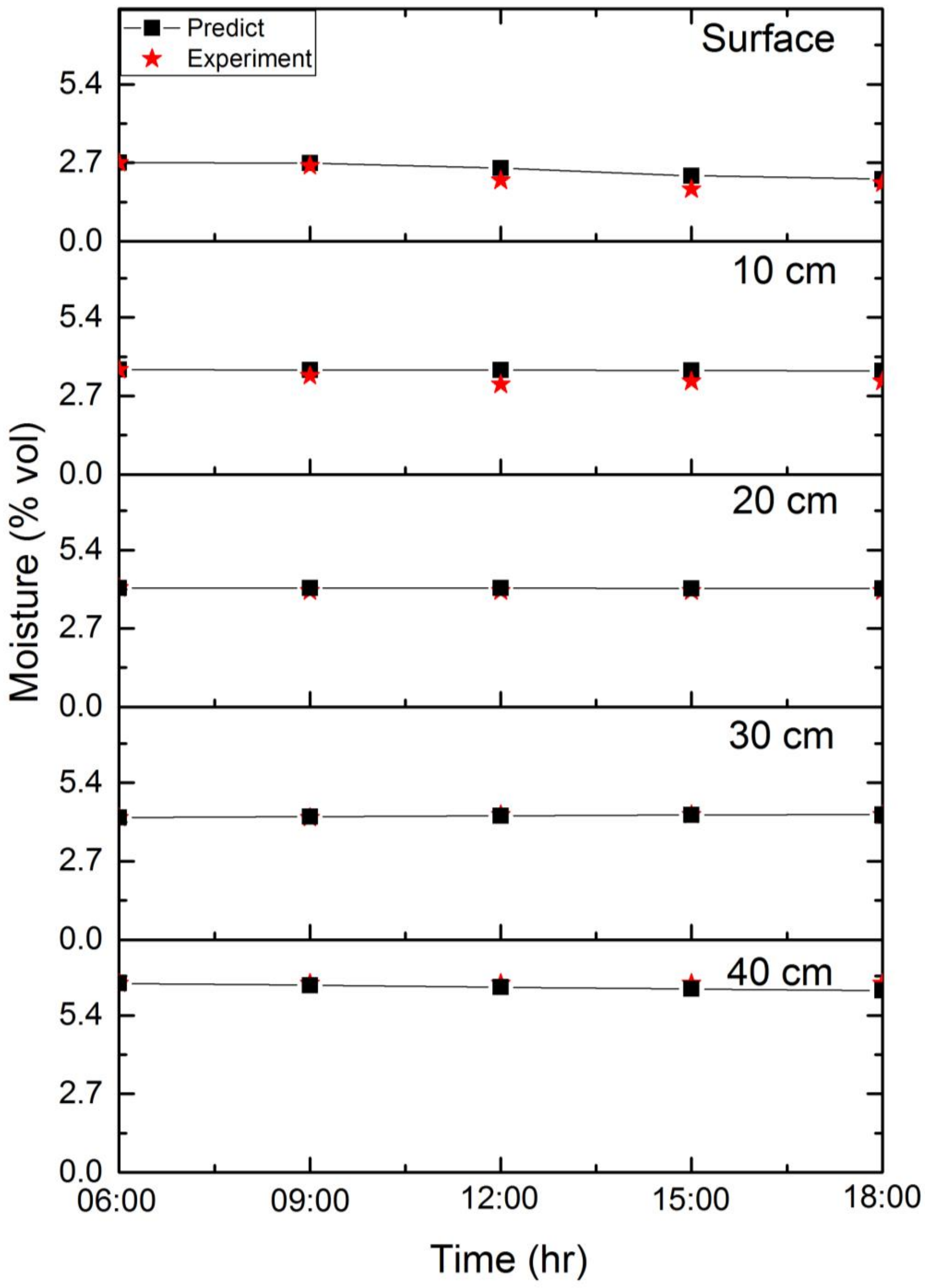

Predict
Experiment
Surface
10 cm
20 cm
30 cm
40 cm
45.0
37.5
30.0
22.5
Temperature (°C)
06:00
09:00
12:00
15:00
18:00
Time (hr)

(a)

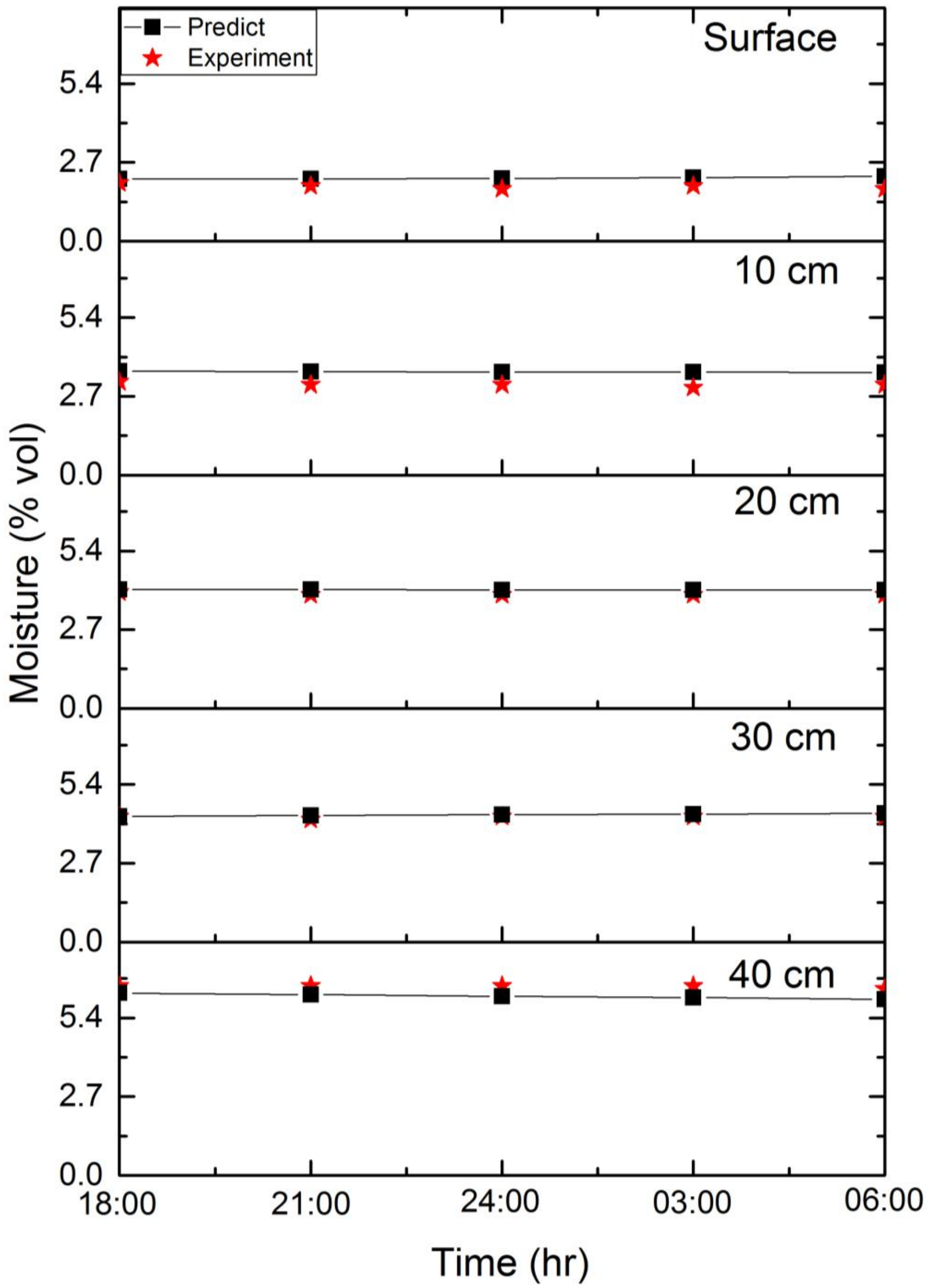


(b)

Figure 3: soil temperature in concrete container at different layers from model and experiment during (a) daytime (b) nighttime


Predict
Experiment
Surface
10 cm
20 cm
30 cm
40 cm
Moisture (% vol)
5.4
2.7
0.0
06:00
09:00
12:00
15:00
18:00
Time (hr)

(a)



(b)

Figure 4: Soil moisture in concrete container at different layers from model and experiment during (a) daytime (b) nighttime

CONCLUSIONS

This mathematical model was found to be able to predict soil temperature and moisture in cylindrical containers of 80 cm in diameter and 40 cm in height. Comparing the soil temperature predicted by the model with measurement from the experiment were found a good agreement throughout the day. The Coefficient of Determination (R^2) were, in general, over 0.8500, which represented the good fit from the model. The Mean Absolute Percentage Error (MAPE) were found to be 0.0111 - 0.0783, which are relatively low. The temperatures at the soil surface showed more variation than at other layers. Furthermore, for the soil moisture, it was found that the results from mathematical model showed relatively low agreement comparing with the temperature results, which may be a result from other affecting factors on moisture in the container. With all findings, this model was found to be reliable in predicting soil temperature and moisture in cylindrical concrete containers. The result would be used as information support for growers to decide which plants are suitable for planting in cylindrical concrete containers and give understanding about the temperature and moisture profile in containers.

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