Thermal Conductivity Prediction of Soil in Complex Plant Soil System using Artificial Neural Networks

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Abstract. Thermal conductivity is one of thermal properties of soil in seed germination and plants growth. Different soil types have different thermal conductivity. One of soft-computing promising method to predict thermal conductivity of soil types is Artificial Neural Network (ANN). In this study, we estimate the thermal conductivity of soil prediction in a soil-plant complex systems using ANN. With a feed-forward multilayer trained with back-propagation with 4, 10 and 1 on the input, hidden and output layers respectively. Our input are heating time, temperature and thermal resistance with thermal conductivity of soil as a target. ANN prediction demonstrates a good agreement with Mean Squared Error-testing (MSE_{te}) of 9.56×10^{-7} for soils with green beans and those of bare soils is 7.00×10^{-7} respectively. Green beans grow only on black-clay soil with a thermal conductivity of 0.7 *W/m K* with a sufficient water content. Our results demonstrate that temperature, moisture content, colour, texture and structure of soil are greatly affect to the thermal conductivity of soil in seed germination and plant growth. In future, it is potentially applied to estimate more complex compositions of plant-soil systems.

1. Introduction

Different soil types have different physical properties. These properties include texture, structure, soil color, soil density, porosity, consistency, viscosity, soil density, temperature and flow of water and air in the soil [1]. These properties indicates thermal properties of soil. These properties relates to soil's microclimate [2]. The soil's microclimate and movement of soil heat control many physical processes on the land-surface such as mass and energy transfer, and biological process such as seed germination and plant growth [2][3]. One of the thermal properties that demonstrate soil ability to conduct heat is thermal conductivity [4].

Thermal conductivity of soil is expressed as weight sum of thermal conductivities of all soil components such as soil organic matter, mineral, water and air [5][6]. It depends on the composition of the soil, moisture content, temperature, and structure of the soil including any factor that affects the heat flow through the soil [7]. Thermal conductivity increase with increasing temperature [8], soil density and moisture content [2].

Since, the reference of soil thermal conductivity has limitation. Here, we compare the thermal conductivity of Jordanian soil. The thermal conductivity of various soil type in Jordanian are shows in Table 1 [2]. Thermal conductivity of soil might be different for another country due to different microclimate. Therefore, our purpose is to investigate the thermal conductivity of soil in Indonesia.

Table 1. Thermal conductivity of Jordanian soil

Soil Types	Thermal conductivity (W/m K)
Sand	0.58 – 1.94
Sandy loam	0.19 – 1.12
Loam	0.29 – 0.76
Clay loam	0.36 – 0.69

There are three heat flow processes occurs on the land surface, such as conduction, convection and radiation. Heat conduction process relate to thermal conductivity. The law of heat conduction is Fourier's Law which states that the rate of heat flow through an object is proportional to the negative temperature and space gradient. It clarifies that heat flux is multiplication product of thermal conductivity with temperature gradient as follows [7]:

$$q = -\kappa \cdot \Delta T \qquad (1),$$

The thermal conductivity, κ ($Wm^{-1}K^{-1}$) of material is a measure of its ability to conduct heat. It defines the amount of thermal energy that is transmitted within a unit time and through a unit cross-sectional area when the temperature gradient across a body is a unit degree (Eq.1) [7]. By considering that thermal resistivity is inverse of thermal conductivity that resist the heat flow [9], hence equation (1) rewrite as follows:

$$\frac{dq}{dt} = \frac{\Delta T}{R} \qquad (2).$$

Conduction process occur on the soil sample in cylindrical dimension, then the heat rate flow in cylinder coordinate in radial direction is given by,

$$\frac{dq}{dt} = -2\pi l \kappa \frac{dT}{dr} \qquad (3),$$

Substituting equation (2) to equation (3) and integrating it, then it yields equation as follows:

$$\kappa = \frac{\ln({r_2}/{r_1})}{2\pi l \cdot R} \qquad (4),$$

In this study, r_2 is radius where thermocouple-2 set in (m), r_1 is radius where thermocouple-1 set in (m), and R is thermal resistance (MΩ).

Physical properties measurement such as temperature and resistance are easier. However, it requires challenging solution to evaluate the measurement result. Thermal conductivity determination requires any temperature measurement simultaneously for each soil types. It could be time-consuming. Therefore, more computational efforts require to estimate thermal conductivity of various soil types. The most popular soft computing methods are genetic algorithm [10] and ANN [11][12].

Reference [12] shows that ANN had been successfully to estimate thermal conductivity and volumetric heat capacity of solid material with average absolute percentage error (APE) 1.216%. His ANN architecture is multi-layer feed-forward trained back-propagation (BP) with 18, 20, and 2 neurons in the input, hidden, and output layer respectively. The transfer function is hyperbolic tangent sigmoid function in hidden layer and linear function in output layer. We adopt reference [12]'s method in this paper by using different types of soil. The soil samples are soil covered green seeds and bare soil. ANN program conducted to cover many soil type. This study presents the thermal conductivity of the soil prediction in a complex system of soil-plant using ANN.

2. Method

Data were collected in July 2015 in Physics Teaching Laboratory, Basic Science Center-A, ITB. Soil samples include black-clay (BC), white-sand (WS), red-loamy (RL), and yellow-dry clay (YC) (see figure 1). Data collection was performed on four different types of soil, each containing 20 seeds of green beans and four types of bare soil. Plant growth is observed for three days without adding water. In this study, we assumed that heat dissipation does not exist. The source of heat came from the stove. We also neglect the thermal conductivity between the cans and the soil. We focused only on the physical changes of green bean seed germination as well.

At the following step, we put each soil type into 500 ml conductor cans. Then, they were heated using water container for 60 minutes. Moreover, we measured the temperature of soil by setting up two Type-K thermocouples (± 0.1 ° C) at depth of 7 cm from the center of the cans. We set the thermocouple in the center of the can and another one in 3.5 cm from the center. The increasing temperature and thermal resistance are recorded every minute. In ANN program, the heating time, temperature and thermal resistance are input data, while thermal conductivity of the soil is target data.

Experimental result provide 488 data from four types of soil with green beans and four types of bare soil. 204 data of soil with green beans are training data and 40 others are testing data. This is also conducted on bare soil to compare its thermal conductivity with soil with green seeds. Our ANN architecture is multi-layer feed forward trained BP with 4, 10, and 1 neurons in input, hidden, and output layer respectively. The function in our architecture is a sigmoid and a linear function (figure 2).

Figure 1. Four types of soil, black clay (top left), white sand (top right), red loamy (bottom left), and yellow clay (bottom right).

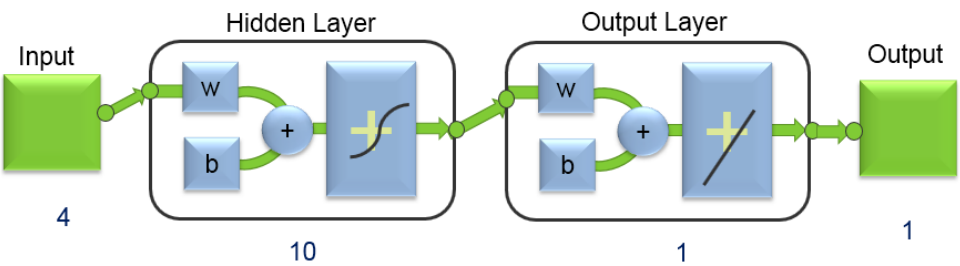
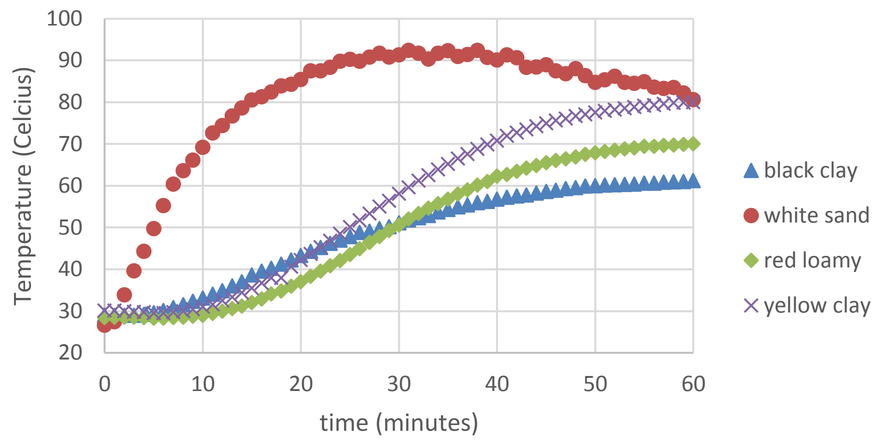


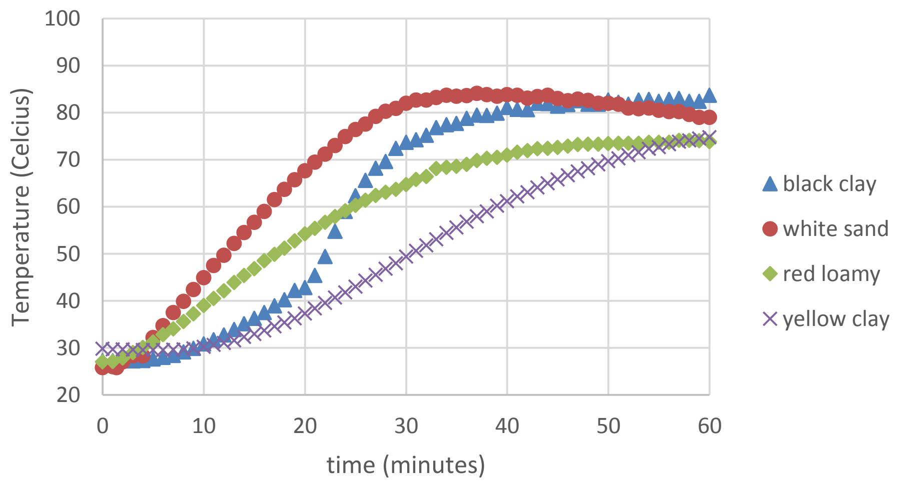
Figure 2. Configuration of multi-layer feed forward for predicting thermal conductivity of soil

3. Result and Discussion

3.1. Experiments Results



(a)



(b)

Figure 3. The increasing temperature of four types of soil, the soil contains green beans (a) and bare soil (b)

Figure 3.a and 3.b demonstrate that green beans decrease the rate of soil's temperature. WS-soil's temperatures increase more significantly than other soil types. Maximum temperature of WS-soil with seeds reach 92.4 °C after 38 minutes. At the same time, bare soil reach 84.1°C after 37 minutes. WS-soil has granules structure, rough texture, and less density. Hence, these properties drive heat transfer and water flow in soil. WS-soil has less water content. Consequently, they decrease the rate of green beans seeds germination. Table 2 shows seed germination conditions for various soil types.

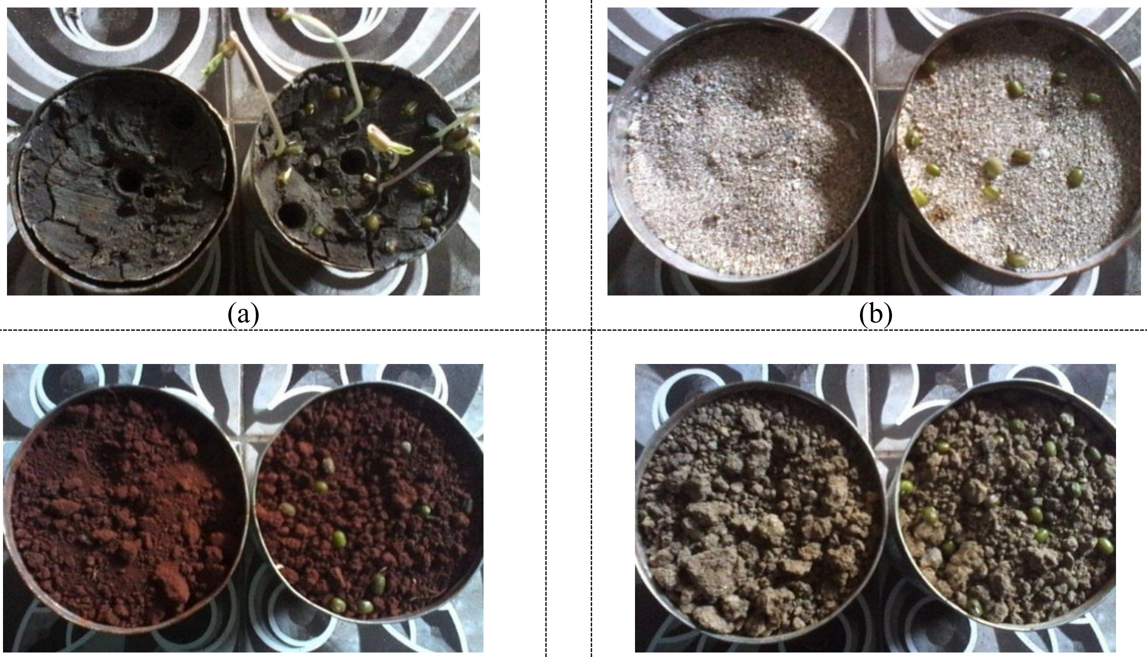
BC-soil's temperature decrease because of green seeds existence. Their maximum temperature reach 61°C after 60 minutes, while for bare soil reach 83.7 °C after 60 minutes. BC-soil contains sufficient moisture content that is required in seed germination. This is an adequate condition for plant growth. Temperature of RL-soil with seed is not different significantly with bare soil.

However, temperature of RL and YC soil reach 70°C after 60 minutes, while bare soil reach 74.0 °C after 60 minutes. YC-soil with seeds has maximum temperature at 80°C after 60 minutes, while those of bare soil is 74.8°C after 60 minutes. These condition are not suitable for plant growth.

Table 2. Soil condition and seed germination for three days

Soil Type	Day	T (°C)	R (MΩ)	Notes
Black Clay	I	25.9	2.196	3 of 20 green seed's root grow
	II	25.6	0.045	10 of 20 green seed's root grow
	III	26.3	0.174	Seed germination grow higher
White Sand	I	26.2	15.09	No seeds grow
	II	27.2	55.10	No seeds grow
	III	29.5	14.60	No seeds grow
Red Loamy	I	27.2	1.487	No seeds grow
	II	29.5	0.659	No seeds grow
	III	29.5	0.569	No seeds grow
Yellow Clay	I	27.5	1.493	No seeds grow
	II	29.3	0.973	No seeds grow
	III	29.5	0.695	No seeds grow

Table 2 shows seed germination for three days. It performs green beans growth only on BC-soil. Theoretically, soil's temperature takes a main role in distribution of nutrition and microbial activity in soil. Temperature and moisture content of soil are required by plants and affects the thermal conductivity of the soil as well. Figure 4 a-d present the soil conditions for three days.

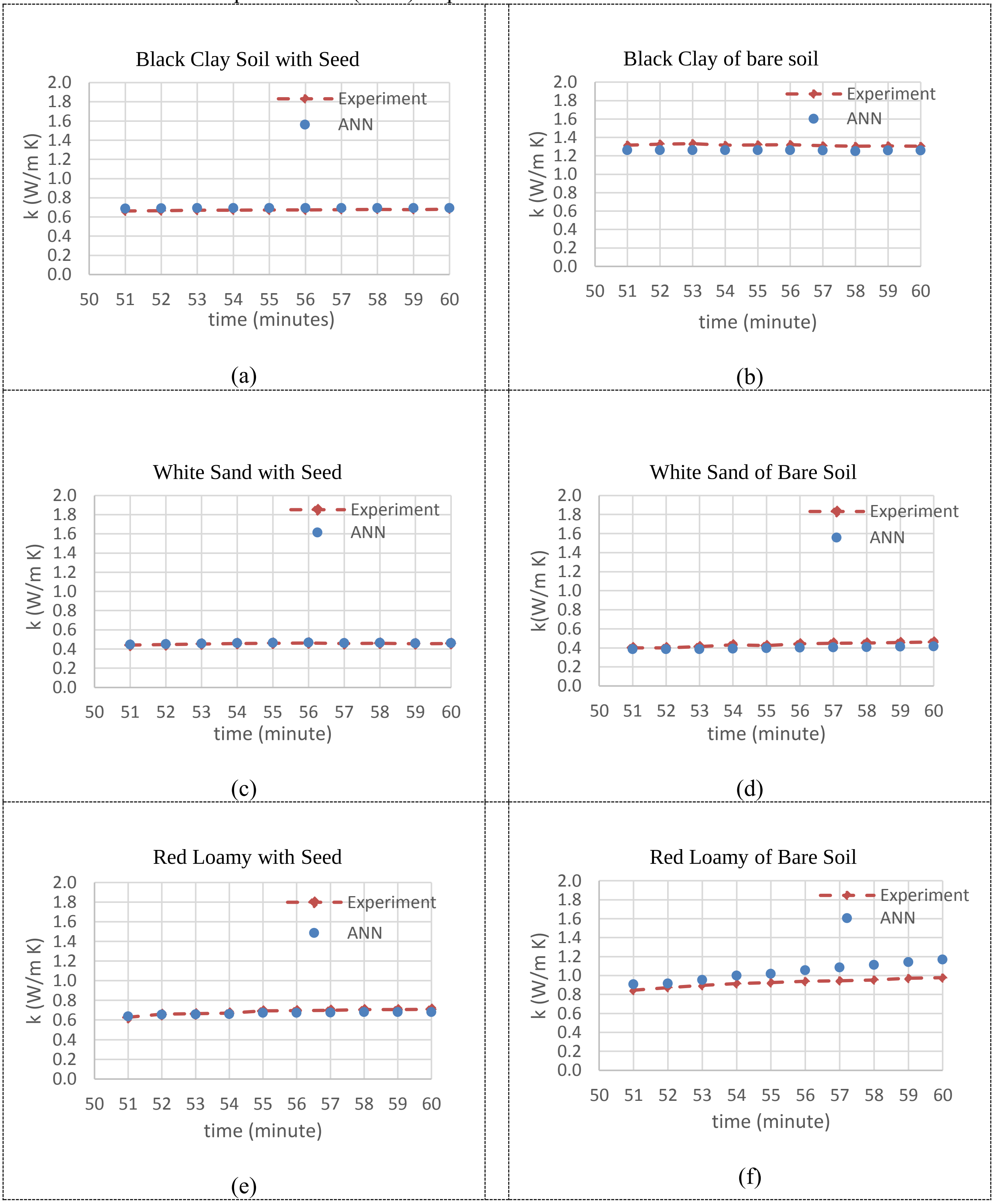


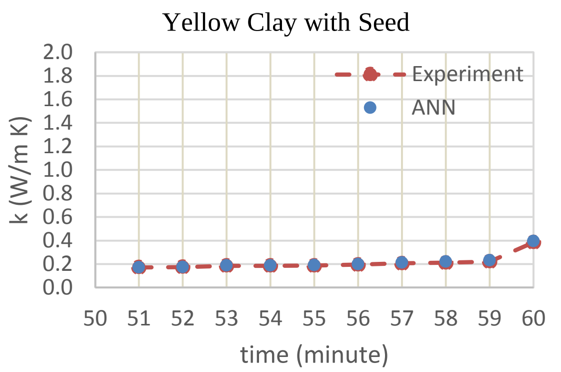
(a) (b) (c) (d)

Figure 4. The heated soil conditions for three days:
(a) Black clay, (b) white sand, (c) red clay, and (d) yellow clay

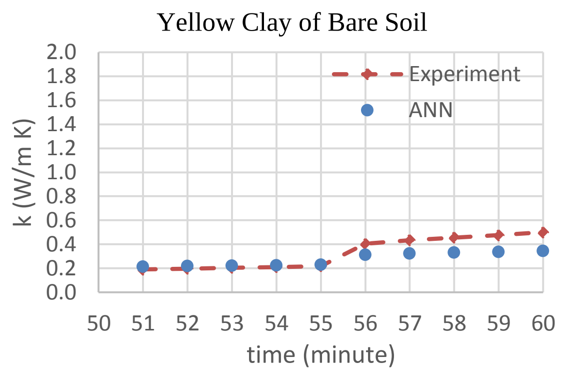
3.2. Prediction of Thermal Conductivity using ANN

Figure 5 performs ANN-BP prediction that tested 10 data from each soil types. Theoretically, thermal conductivity of soil is calculated by performing equation (4). The predicted results are compared with experimental data to measure thermal conductivity. It is conducted to validate the predictions result. Table 2 shows Mean Squared Error (MSE) of prediction.



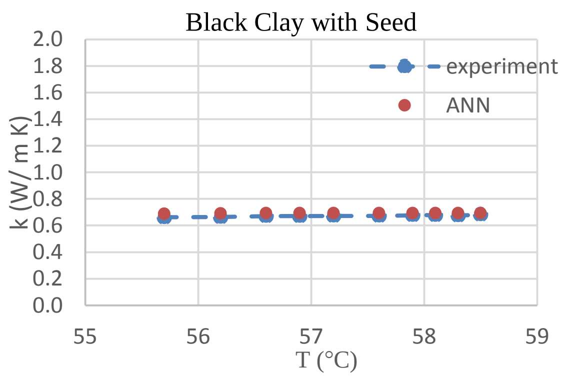


(g)

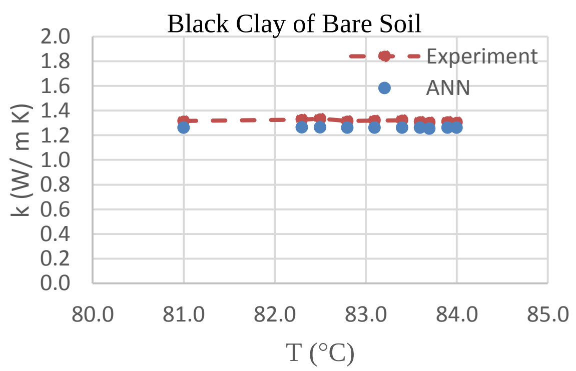


(h)

Figure 5. Thermal conductivity of soil prediction using ANN as function of time: soil with seed : (a) black clay; (c) white sand; (e) red loamy; (g) yellow clay; and bare soil (b) black clay; (d) white sand; (f) red loamy; and (h) yellow clay.



(a)



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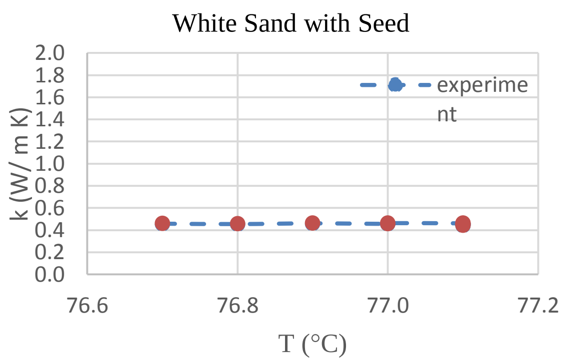

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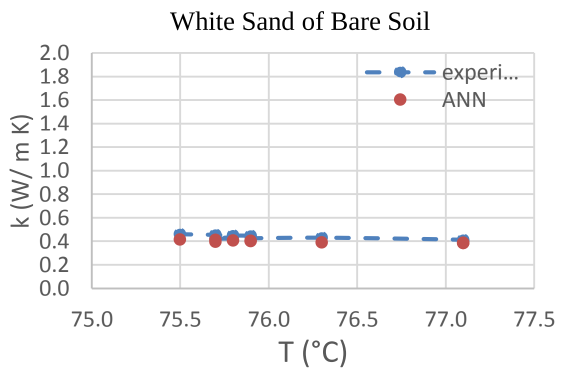

(d)

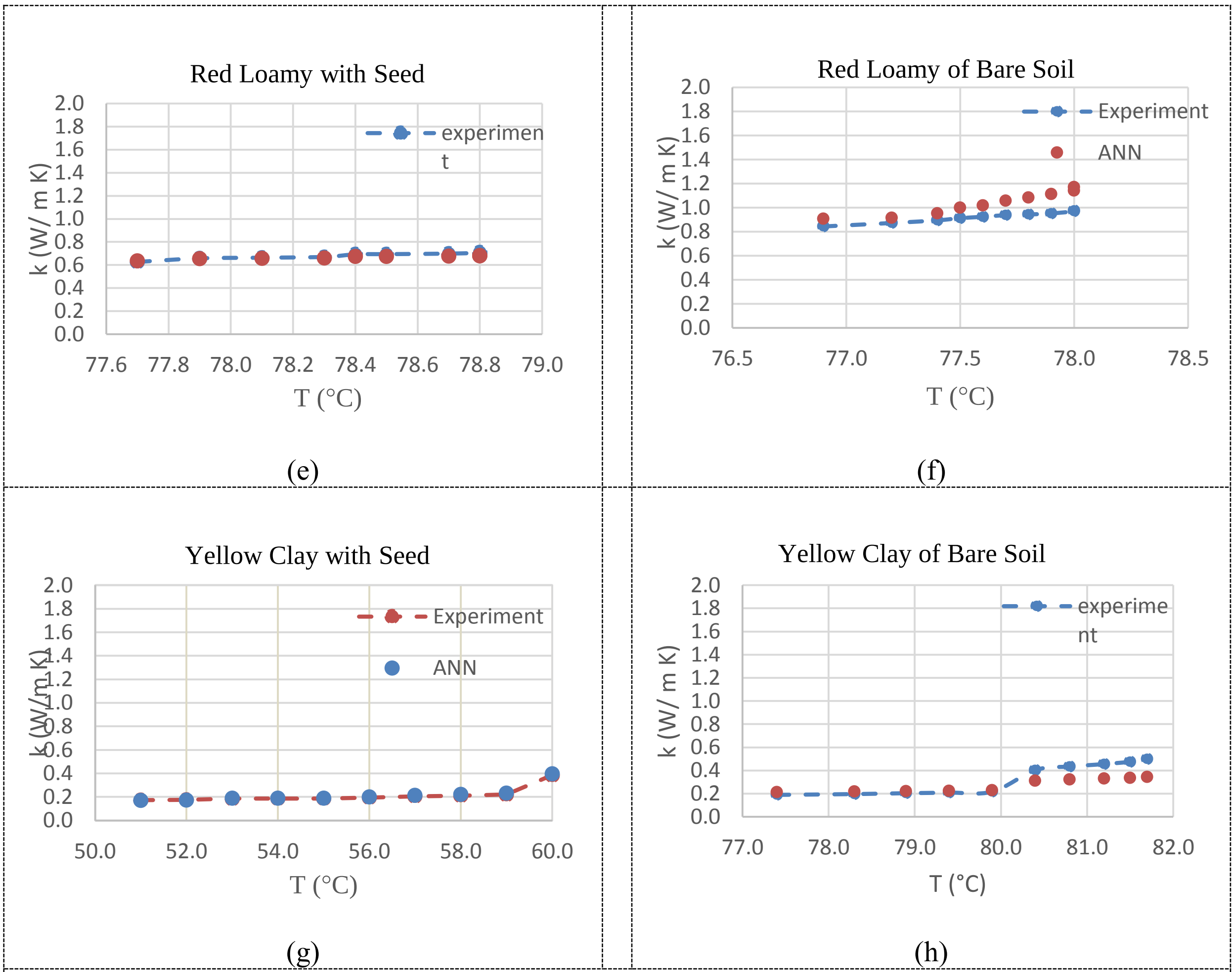

Figure 6. Thermal conductivity of soil prediction using ANN as function of temperature: soil with seed : (a) black clay; (c) white sand; (e) red loamy; (g) yellow clay; and bare soil (b) black clay; (d) white sand; (f) red loamy; and (h) yellow clay.

Table 3. The average error of the soil with seeds and bare soil

Soil	MSE-training	MSE-Validation	MSE-testing
Soil contain green seeds	1.97×10^{-7}	1.31×10^{-6}	9.64×10^{-7}
Bare soil	2.63×10^{-7}	0.83×10^{-6}	7.00×10^{-7}

ANN-BP prediction shows a good agreement with experimental result of thermal conductivity of soil. Although the prediction of RL-soil and YC-soil with seeds (figure 5.f and 5.h) show less satisfactory, the results provide good accuracy for other soil types. It shows that MSE-training for soil with green seeds is 1.97×10^{-7}, MSE-validation is 1.31×10^{-6}, and MSE-testing is 9.64×10^{-7}. Furthermore, the MSE-training, MSE-validation, and MSE-testing for bare soil are 2.63×10^{-7}, 0.83×10^{-6}, and 7.00×10^{-7} respectively.

Figure 5 and 6 demonstrates thermal conductivity differences of soil with seeds compared with bare soil. The difference of thermal conductivity of BC-soil is significant (figure 5a and 5b). It is about 0.7

W/m K for BC-soil with green beans and 1.3 *W/m K* for BC of bare soil. Thermal conductivity depends on temperature, moisture content, and other factors that affect the heat flow through the soil e.g. green seeds existence. BC-soil contains high water content. This condition is important to construct a soil-plant system. On the other case, green bean seeds are not able to grow on WS, RL and YC-soil because their soil is dry. The green seeds reduce heat energy in the soil. The amount of energy depends strongly on soil color, aspect, and vegetative cover [13]. Therefore, thermal conductivity of soil with seed is lower than bare soil (figure 5 and 6).

Thermal conductivity prediction of RL and YC of bare soil perform does not have good fit with experiment result (5.f and 5.h). It requires to further investigation by reviewing data and retraining ANN program. Nevertheless, the predictions present a good agreement with experimental result for other soil types. Although the thermal conductivity of RL-soil with seeds is equal to BC-soil, the green bean seeds do not grow successfully. Moisture content of RL-soil is less than those of BC-soil.

4. Conclusion

Thermal conductivity of soil prediction using ANN performs a good agreements with experimental result. The MSEte is 9.56×10^{-7} for soil with green beans and those of bare soil is 7.00×10^{-7} respectively. Therefore, ANN successfully predict the thermal conductivity of soil. Thermal conductivity of soils with seeds are lower than those of bare soil because of strongly vegetative cover dependent. Moisture content, color, structure and texture of soil should be considered in thermal conductivity determination. Green beans grow only on black clay soil with thermal conductivity of 0.7 *W/m K* with sufficient moisture content.

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