
Measurement of Soil Thermal Conductivity as A Basis for Selecting Soil Types for Photovoltaic Passive Cooling Systems

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Keywords:

Soil Thermal Conductivity;
Transient Line Heat Source;
ESP32; DS18B20; Passive Cooling

Abstract

This study aims to measure and analyse the thermal conductivity of clay and sandy soils as potential media for passive cooling systems in photovoltaic modules. A quantitative experimental approach was employed using the Transient Line Heat Source (TLS) method, which utilises the temperature response over time due to a linear heat source. The measurement system was developed using an ESP32 microcontroller integrated with a DS18B20 temperature sensor capable of real-time data acquisition. The results indicate that the system operates in an integrated manner and produces stable data for thermal conductivity calculations. The thermal conductivity of clay soil was found to be 1.133 W/mK at a moisture content of 74.25%, while coastal sandy soil exhibited a higher value of 1.595 W/mK at a moisture content of 81.25%. Sandy soil demonstrated approximately 40.78% higher heat transfer capability compared to clay soil. These findings suggest that, in addition to soil type, moisture content plays a significant role in determining thermal conductivity. Soils with higher moisture content therefore hold greater potential as passive cooling media for enhancing the efficiency of photovoltaic systems.

INTRODUCTION

The ever-increasing global energy demand is driving various countries to accelerate the development of more sustainable and environmentally friendly renewable energy sources, one of which is solar energy through photovoltaic (PV) technology (Haegel & Kurtz, 2025). Photovoltaic technology is developing rapidly because it can convert solar radiation directly into direct current (DC) electrical energy that can be used for various modern energy needs (Saravanan et al., 2024). In addition to having an abundant energy source, PV systems are also considered more efficient, easy to implement, and able to provide an independent electricity supply without relying entirely on the conventional electricity grid (Jahan et al., 2025). The use of this technology is increasingly widespread, ranging from solar-based street lighting systems, household-scale power plants, to independent electricity systems in remote areas that are not yet reached by the main electricity distribution network. (Pongoh et al., 2025; Rustiyana, 2025).

Photovoltaic applications are highly suitable for tropical countries like Indonesia, which is located on the equator and receives sunlight almost year-round. This geographical location provides Indonesia with enormous solar energy potential for development as a future energy source. Solar radiation intensity in some regions of Indonesia reaches 4.5–5.8 kWh/m² per day, providing significant opportunities for developing more optimal and sustainable solar power generation systems (Martin et al., 2022). With this potential, PV technology is a strategic solution to support

the national energy transition towards clean energy and reducing dependence on fossil fuels (Breyer et al., 2018; Lazaroiu et al., 2023; Swadi et al., 2024; Triani et al., 2024).

However, solar panel performance still faces a major challenge in the form of increased module operating temperature, which can significantly reduce output power efficiency. During the process of absorbing solar radiation, some of the energy received by the photovoltaic panel is not entirely converted into electrical energy, but instead turns into heat energy that accumulates on the module surface. This heat accumulation causes the panel temperature to increase as solar radiation intensity changes throughout the day. This temperature increase directly impacts the electrical characteristics of the solar cell, particularly the decrease in output voltage, which results in decreased electrical energy conversion efficiency (Dubey et al., 2013). In monocrystalline silicon solar panels, a 1°C temperature increase can reduce output power by approximately 0.5%, so a temperature increase of up to 10°C has the potential to reduce panel output power by approximately 5% (Libra et al., 2021). This condition indicates that operating temperature is one of the most important parameters affecting the stability and performance of a photovoltaic system (Al-Ghezi et al., 2022; Hasan et al., 2022; Rahman, 2022).

One potential approach is grounding-based passive cooling by utilizing soil as a heat-dissipating medium. The ability of soil to conduct heat is determined by its thermal conductivity value, which is influenced by various factors such as soil type, water content, density, soil structure, and chemical conditions such as pH (Majeed et al., 2023). Meanwhile, the characteristics of soil microstructure are also influenced by pH and humidity values, which can affect the heat propagation process (Lunt et al., 2023); (Haas & Horn, 2018); (Wang et al., 2023). Therefore, the thermal characteristics of the soil cannot be determined solely based on the soil type, but are the result of the interaction of various physical and chemical parameters of the soil.

However, most previous studies remain general in nature and have not specifically compared the heat conduction capabilities of particular soil types by considering physical and chemical parameters simultaneously in the context of photovoltaic cooling applications. Research is therefore needed that can provide empirical data more representative of actual field conditions, particularly in determining the most effective soil type as a passive cooling medium. Against this background, this study aims to analyse and compare the thermal conductivity values of clay and sandy soils using the Transient Line Heat Source method, and to examine the effect of moisture content and pH on heat conduction capability. The study also evaluates the reliability of the DS18B20 temperature sensor in the measurement process to ensure the accuracy of the data obtained. Through a microcontroller-based experimental approach, this study is expected to provide a scientific basis for the selection of optimal soil media for passive cooling systems in photovoltaic modules.

The novelty of this research lies in the integration of thermal conductivity analysis of two soil types by considering physical and chemical parameters simultaneously, as well as the application of a transient measurement method based on a real-time data acquisition system, in support of the development of more effective and practically applicable passive cooling systems.

This research contributes to the growing body of knowledge on passive cooling strategies for photovoltaic systems, which is of particular relevance for tropical countries where thermal management is critical for maintaining system efficiency. The findings are expected to inform the selection of suitable soil types for grounding-based passive cooling applications, potentially

improving the economic viability and performance of photovoltaic installations in regions with high solar irradiance.

RESEARCH METHODS

This study adopted a quantitative experimental systems approach, applying this approach to the creation of a measurement system and data analysis. This study compared the heat conductance values of clay and sandy soil, as well as their moisture content and pH.

Hardware Design

The main instrument used in this study is a measurement system based on the Transient Line Heat Source method integrated with an ESP32 microcontroller. The system consists of a DS18B20 temperature sensor to measure temperature changes continuously, a heating element as a linear heat source, a power supply to maintain power stability, and soil moisture and pH sensors to measure soil supporting parameters with the setup referred to in Figure 1. All components are integrated through programming using the Arduino IDE to enable real-time data acquisition.

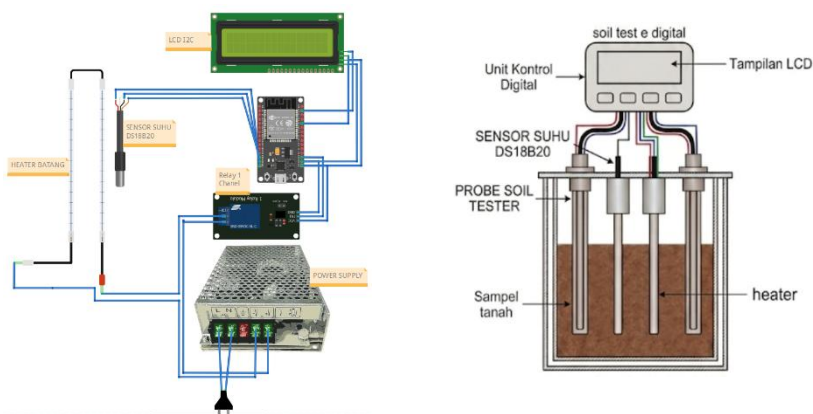


Figure 1. Measurement Setup

System Block Diagram

The system block diagram consists of three main parts: input, process, and output, which are integrated to measure soil thermal conductivity. The input section contains two main components: a heater and a DS18B20 temperature sensor. The heater functions as a linear heat source embedded in the soil to generate heat flow. When the heater is activated, heat will radiate to the surrounding soil environment. Meanwhile, the DS18B20 sensor measures changes in soil temperature due to the heating. The resulting temperature data is a function of time (T versus t), which is the main parameter in the transient method.

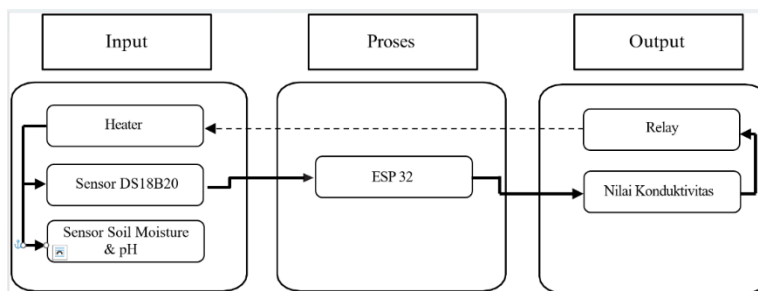


Figure 2. System Block Diagram

System Flowchart

The system flowchart in Figure 1 & 2 illustrates the workflow starting from the initialization of all components, then the system activates the heater as a heat source to heat the soil media, the temperature sensor continuously reads changes in temperature over time (T and t), then the system checks the conditions until the temperature reaches the desired state, after which the temperature and time data obtained are processed by ESP32 using the transient method to calculate the thermal conductivity value (λ).

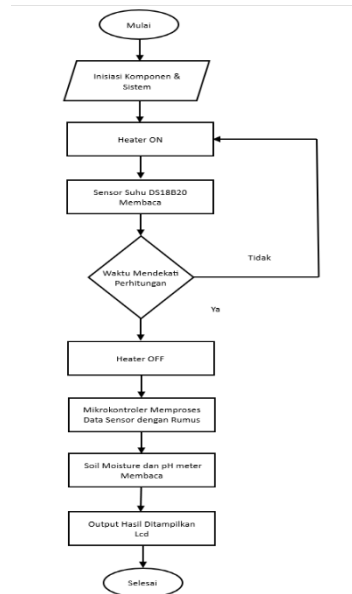


Figure 3. System *Flowchart*

Implementation of Measurement System

Data collection is carried out automatically by the system by recording pairs of temperature (T) and time (t) values over a certain interval. The collected data is then analyzed using the transient method equation to determine the thermal conductivity value. In the analysis, two data points (start and end) are used to describe the temperature variation over time. To maintain data validity, the system only processes data that have a positive temperature difference ($\Delta T > 0$), thus avoiding calculation errors. The measurement system uses the following equation:

$$\lambda = \frac{Q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad (1)$$

The implementation of this calculation is directly embedded in the ESP32 program, which first calculates the temperature difference ($\Delta T = T_2 - T_1$) to ensure data validity. The results of the thermal conductivity calculation are then displayed via serial communication and can be displayed on the LCD as system output.

```

147 // =====
148 // HITUNG KONDUKTIVITAS
149 // =====
150 void hitungKonduktivitas() {
151
152     float t1 = tData[10];
153     float t2 = tData[17];
154     float T1 = TData[10];
155     float T2 = TData[17];
156
157     float deltaT = T2 - T1;
158
159     if (deltaT <= 0) {
160         Serial.println("Delta T tidak valid!");
161         return;
162     }
163
164     float k = (Q / (4 * PI * deltaT)) * log(t2 / t1);
165
166     Serial.println("----- HASIL PERHITUNGAN -----");
167     Serial.print("k = ");
168     Serial.println(k);
169     Serial.println(" W/mK");
170
171     lcd.clear();
172
173     lcd.setCursor(0, 0);
174     lcd.print("T1=");

```

Figure 4. Program Code

Heat flux conversion

The heat power generated by the heating element is then converted into a linear heat flux to represent the distribution of the heat source throughout the test medium. This conversion is performed by comparing the heat power to the length of the heating element, resulting in a heat flux parameter that forms the basis for the Transient method analysis.

$$Q = \frac{W}{L} \tag{2}$$

with Q as linear heat flux (W/m), W as heat power, and L as length of heating element. This value is used as the main parameter in the calculation of thermal conductivity because it reflects the rate of heat distribution along a linear heat source.

RESULTS AND DISCUSSION

System Design Results

The system design results in this study are an implementation of a transient-based soil thermal conductivity measurement method. The system design was carried out by integrating hardware and software to produce a measurement system that works automatically, accurately, and stably in recording temperature change data.



Figure 5. *Prototype of Conductivity Measurement System*

over time. This system consists of an ESP32 microcontroller as the control center, a DS18B20 temperature sensor as a temperature gauge, a heating element as a heat source, a relay as an electrical contactor on the heating element, and a soil tester sensor to measure soil moisture and pH.

In its implementation, the system is used to measure the thermal characteristics of clay and sandy soil. The heater functions as a heat source that generates heat propagation in the soil, while the DS18B20 sensor reads temperature changes over time. The data obtained is then processed to determine the thermal conductivity value using the Transient method. Overall, the designed system has functioned well, where all components can be integrated and work automatically. The system is also capable of recording temperature data continuously and generating thermal conductivity values. Showing the measurement setup for edge points and midpoints in the thermal conductivity measurement test.

Transient Conduction Test Results

Based on the analysis of the temperature versus time graph, it can be concluded that the heat transfer process occurring in the clay and coastal sandy soil media exhibits transient heat transfer characteristics. This is indicated by the appearance of a significant temperature increase at the start of heating, which is then accompanied by a decrease in the rate of temperature increase over time.

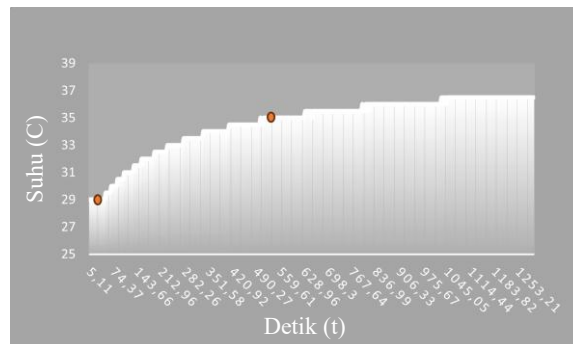


Figure 6. *Transient Conduction Measurement Graph*

The most representative time range for describing transient conditions in both soil types is approximately 37 seconds to 540 seconds. During this time, significant temperature changes still occur, so the data obtained reflects a heat transfer process that has not yet reached a steady state.

Therefore, this time interval can be considered ideal for data collection for transient heat transfer analysis.

Heater Power Test Results

The heater power stability test in this study was conducted to determine the accuracy of the heater power used for 10 minutes, to obtain a stable heat flux value to maintain system reliability, by dividing the heating power by the length of the heater element (0.15 meters). To obtain the power value, the voltage and current of the heater element were measured.

Table 1. Heater Heat Flux Results

No	Voltage(V)	Current(A)	Power(W)	Q (W/m)
1	11.93	0.35	4.17	27.8
2	11.93	0.35	4.17	27.8
3	11.93	0.35	4.17	27.8
4	11.93	0.35	4.17	27.8
5	11.91	0.35	4.16	27.7
6	11.93	0.35	4.17	27.8
7	11.91	0.35	4.16	27.7
8	11.93	0.35	4.17	27.8
9	11.95	0.35	4.18	27.8
10	11.93	0.35	4.17	27.8
Average			4.17	27.78

Based on Table 1, the voltage during the test was in the range of 11.91–11.95 V and the current remained constant at 0.35 A. This condition resulted in almost unchanged power, namely 4.16–4.18 W with an average of 4.17 W. The heat flux (Q) value was also relatively uniform, in the range of 27.7–27.8 W/m with an average of 27.78 W/m. The very small difference between the data is thought to originate from slight fluctuations in the voltage source. However, the power that tends to be constant indicates that the heater is working stably. This is important because power stability directly affects the uniformity of heat flux, so that the temperature distribution within the material can be observed more consistently .

DS18B20 Temperature Sensor Accuracy Test Results

Sensor accuracy testing in this study was conducted to determine the accuracy of the temperature sensor readings used, namely the DS18B20 sensor, by comparing the measurement results to a reference device, namely IR thermography. This testing aims to ensure that the temperature data used in the thermal conductivity analysis is reliable.

Table 2. DS18B20 Temperature Sensor Accuracy

No	DS18B20	IR Thermography	Error (%)	Accuracy (%)
1	32	32.4	1.23%	98.77%
2	36	36.4	1.09%	98.91%
3	38	38.8	2.06%	97.94%
4	39	39.5	1.26%	98.74%
5	42	42.2	0.47%	99.53%
6	44.5	45	1.11%	98.89%
7	49	49.8	1.60%	98.40%
8	50.5	51	0.98%	99.02%
9	52.5	53.3	1.50%	98.50%
10	53.5	53.9	0.74%	99.26%
Average			1.20%	98.79%

Based on Table 2, the DS18B20 temperature sensor measurements compared to IR Thermography show fairly close results, with small differences at each point. The error value is in the range of 0.47%–2.06% with an average of 1.20%, where the highest error occurs in the 3rd measurement and the lowest in the 5th measurement. This difference is thought to be influenced by the characteristics of the sensor response and environmental conditions during the measurement process. In terms of accuracy, the DS18B20 shows good performance with values between 97.94%–99.53% and an average of 98.79%. The sensor also remains consistent at higher temperature ranges. In general, the deviations that occur are still within reasonable limits, so this sensor can be considered adequate for use in temperature measurements in heat transfer research.

Experimental Test Results

Experimental testing was conducted on clay and sea sand for 9 minutes under transient conditions, with depth variations of 10 cm and 20 cm at the center and edge measurement points. Data obtained included test time, pH, humidity, temperature changes, heat flux, and thermal conductivity values.

Clay Test Results

The results of the system design and test data conducted on the transient-based soil thermal conductivity measurement system are a crucial part of this research. The process involved several stages, from hardware design and integration of components such as temperature sensors and heaters, to testing on various soil types and conditions. Each stage was carried out in stages to ensure the system would perform well and produce consistent data. The test data was used to determine the soil's thermal conductivity based on its temperature response to heat flux during transient conditions. The analysis was performed by observing temperature changes over time to determine the relationship between heat distribution and the material's thermal conductivity. The consistency of the data obtained also indicates that the system is capable of producing relatively stable conductivity values.



Figure 7. Clay Testing

Table 3. Clay Testing

No	Testing Time	Points & Depth (cm)	pH	Humidity (%)	Temperature Change (C)	Heat Flux	Conductivity (W/mK)
1	9 minutes	Midpoint - 10 cm	5.3	73%	6°C	27.8	1,077
2	9 minutes	Edge point - 10 cm	6.1	84%	4°C	27.8	1,481
3	9 minutes	Midpoint - 20 cm	5.3	70%	6°C	27.7	0.987
4	9 minutes	Edge point - 20 cm	6.3	70%	6°C	27.8	0.987
Average			5.7	74.25%	5.5°C	27.7	1,133

This table shows the results of clay thermal conductivity measurements based on point and depth variations. The values are in the range of 0.987–1.481 W/mK, with an average of 1.133 W/mK. This condition is influenced by soil moisture ranging from 70%–84% and a pH of 5.3–6.3. In addition, temperature changes that occur are in the range of 4–6°C with an average of 5.5°C, and the heat flux is relatively stable at around 27.7–27.8 W/m with an average of 27.7 W/m. The thermal conductivity results are still in accordance with the literature, where the thermal conductivity of clay soil is in the range of 0.85–1.4 W/mK (Sub-district & Kalimantan, 2020). The variation in values obtained is related to water content and soil structure. Increasing moisture tends to increase the soil's ability to conduct heat, consistent with previous research that identified water content as a major factor in thermal conductivity.

In testing, higher humidity results in higher conductivity values because water acts as a heat conductor. Conversely, at lower humidity, conductivity values decrease. Furthermore, differences in measurement points and depths (10 cm and 20 cm) also affect the results. The midpoint tends to show more stable values, while the results at the edges are more variable, influenced by humidity.

Coastal Sand Soil Test Results

Observations on coastal sandy soil in this study were conducted to analyze the characteristics of the soil's thermal conductivity by considering moisture and pH parameters. This analysis aims to determine the relationship between the physical condition of the soil and its ability to conduct heat based on the test data obtained. Furthermore, observations were conducted in stages, observing

changes in temperature over time during the heating process, thus obtaining a clearer picture of the heat propagation mechanism in the soil medium. The resulting data were then processed using a thermal conductivity calculation method to obtain representative values. The results of this analysis are expected to demonstrate how soil conditions vary, particularly moisture and pH levels.



Figure 8. Coastal Sand Soil Testing

Table 4. Coastal Sand Soil Testing

No	Testing Time	Points & Depth (cm)	pH	Humidity (%)	Temperature Change (C)	Heat Flux	Conductivity (W/mK)
1	9 minutes	Midpoint - 10 cm	5.8	86%	3°C	27.8	1,786
2	9 minutes	Edge point - 10 cm	6.1	79%	4°C	27.7	1.48
3	9 minutes	Midpoint - 20 cm	6	80%	4°C	27.8	1.55
4	9 minutes	Edge point - 20 cm	5.9	80%	4°C	27.8	1,566
Average			5.9	81.25%	4°C	27.7	1,595

This table displays the results of coastal sandy soil thermal conductivity measurements based on various points and depths. The values range from 1,480–1,786 W/mK, with an average of 1,595 W/mK. Soil moisture ranges from 79%–86%, while pH ranges from 5.8–6.1. In addition, temperature changes occur within the range of 3–4°C with an average of 4°C, and heat flux is relatively stable at around 27.7–27.8 W/m with an average of 27.7 W/m. These thermal conductivity results are consistent with previous research, where the thermal conductivity of granular soil is in the range of 1–3 W/mK (Library et al., 2022). This condition indicates that the data obtained is still in line with the general characteristics of sandy soil, thus supporting the reliability of the research results.

Given these findings, it is evident that humidity significantly impacts thermal conductivity values. Under the highest humidity conditions of 86%, a peak conductivity value of 1,786 W/mK was achieved. This indicates that the higher the water content in the soil, the greater the soil's ability to conduct heat. Furthermore, the relatively stable soil pH value in the range of 5.8 to 6.1 indicates that pH does not significantly influence changes in thermal conductivity values. However, pH

remains a supporting parameter in describing soil conditions during testing. Differences in measurement points and depths also show variations in conductivity values, but these changes are not as significant as the influence of humidity. This indicates that the main factor influencing the test results is the water content in the soil. Overall, the test results indicate that coastal sandy soil has good heat conductivity under high humidity conditions.

Comparative Analysis of Coastal Clay and Sandy Soil Test Results

Comparative analysis of test results on two types of soil media (clay and coastal sand) shows significant differences in heat conduction capabilities, where the thermal conductivity values obtained reflect the influence of material characteristics and water content on the heat propagation process in each media.

Furthermore, the internal structural characteristics of the soil also influence the rate of heat transfer, so each soil type responds differently to a given heating process. Soil with better heat conductivity will exhibit a faster and more stable temperature increase, while soil with lower heat conductivity tends to experience slower heat transfer.

Table 5. Comparison of the Two Lands

No	Data	Clay	Coastal Sandy Land
1	pH	5.7	5.9
2	Humidity	74.25%	81.25%
3	Conductivity (W/mK)	1,133	1,595
4	Information	Tends to have low humidity so that it affects the conductivity value, the pH value also decreases.	Tends to have higher humidity than clay, thus affecting the higher conductivity value, the pH value also increases.

Based on the test results in Table 4.3.3, the thermal conductivity (k) value for clay is 1.133 W/mK, while for coastal sandy soil it is 1.595 W/mK. This value indicates that coastal sandy soil has a better ability to conduct heat than clay. To determine the level of difference in heat conduction ability between the two media, the calculation of the percentage increase in thermal conductivity is used.

with the formula:

New value–Reference value

$$\% \text{ Perbedaan} = \frac{\text{Reference value}}{\text{Reference value}} \times 100\%$$

$$\% \text{ Perbedaan} = \frac{k_{pasir} - k_{liat}}{k_{liat}} \times 100\%$$

Value substitution:

$$= \frac{1.595 - 1.133}{1.133} \times 100\% = 40.78\%$$

Calculation results show that the thermal conductivity of coastal sandy soil is approximately 40.78% higher than that of clay. This difference is influenced by the material characteristics of each

soil and its water content. Coastal sandy soil has a higher moisture content (81.25%) than clay (74.25%), thereby accelerating the heat transfer process. The water content in the soil acts as a good heat conductor, so the higher the humidity, the higher the thermal conductivity value. Conversely, clay soil shows a lower conductivity value because the heat propagation process occurs more slowly in this medium, so its ability to conduct heat is not as good as coastal sandy soil.

CONCLUSION

Based on the results of the design, implementation, and testing of the system, this study shows that the microcontroller-based soil thermal conductivity measurement system has worked in an integrated manner and is capable of automatically acquiring temperature data well. The DS18B20 sensor has proven responsive in recording temperature changes in real-time, so it can be used to calculate thermal conductivity values accurately. The test results show a difference in thermal conductivity between clay and coastal sandy soil, where sandy soil has a higher conductivity value (1,595 W/mK) compared to clay (1,133 W/mK), or an increase of about 40.78%. This difference is influenced by the humidity level, where the higher water content in sandy soil accelerates the heat propagation process. Thus, it can be concluded that in addition to soil type, the humidity factor has an important role in determining the ability to conduct heat, so it has the potential to be used as a passive cooling medium in photovoltaic systems.

For further research, it is recommended that the analysis be expanded by adding other physical parameters such as soil porosity and density to gain a more comprehensive understanding of the soil's thermal characteristics. Furthermore, regular temperature sensor calibration is necessary to improve data accuracy and stability. The analysis method can also be improved by incorporating additional relevant variables and increasing the number of temperature measurement points to allow for a more comprehensive observation of heat distribution. Further research should also include various soil types with varying characteristics to enhance the validity of the results. Furthermore, system integration with an Internet of Things (IoT)-based platform equipped with real-time data visualization is highly recommended to facilitate the monitoring and analysis process more effectively and efficiently.

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