REAL-TIME CURRENT-VOLTAGE CURVE-BASED ON-FIELD VALIDATION OF PHOTOVOLTAIC PERFORMANCE FOR AN ELEPHANT DETERRENT SYSTEM

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ABSTRACT

On-field monitoring systems for assessing the performance of solar photovoltaic systems in remote or off-grid settings remain limited under tropical outdoor conditions. This work developed and validated a low-cost Arduino-based current-voltage curve tracer to monitor the performance of monocrystalline and polycrystalline solar panels for a dependable unit power supply. The tracer system used an Arduino UNO, an INA219 current sensor, an F301-06 voltage sensor, and a 470 µF capacitive load to capture real-time current, voltage, and power data through Microsoft Excel Data Streamer. The system was validated against a digital multimeter (Fluke 175) and tested in the field for 10 days under irradiance levels of 789-1270 W/m² and ambient temperatures up to 33 °C. Validation showed a mean voltage error of approximately ±0.72% and a mean current error of 8.18%. As a comparison, the monocrystalline panel produced higher output on 8 of 10 days and reached a maximum power output of 10.8 W, while the polycrystalline panel performed better on two lower-irradiance days. The measured photovoltaic output was sufficient to meet the estimated average load of the low-power deterrent unit including sensors, controllers and sound-emitting devices, which indicates that the proposed monitoring approach is practical for solar-powered wildlife deterrent applications in off-grid locations.

Keywords: current-voltage (I-V) curve, Arduino-based tracer, monocrystalline, polycrystalline, capacitive load, Data Streamer, deterrent system

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1. INTRODUCTION

The installation of photovoltaic (PV) systems as one of the renewable energy solutions has kept rising in the last few years, as they have been identified as an important renewable energy source due to their continuous availability with minimal waste production and capacity for decentralized power generation [1]. The Earth receives approximately 1366 W/m^2 of solar irradiance, where it becomes an infinite energy source and a free resource for remote and off-grid applications [2]. As a result, many researchers worldwide are working in this field to contribute current knowledge about this technology and improve its cost-effectiveness [3].

However, conventional solar panel technologies still face challenges such as low energy conversion efficiency and difficulties with thermal management across different climates. Climate conditions and operating temperatures directly affect the efficiency and durability [4]. These factors can significantly impair system performance, especially in outdoor environments such as wildlife conservation areas, where robust and autonomous power systems are essential. In such remote application systems, solar-powered virtual or automated elephant deterrent systems depend on the reliable functioning of PV modules to operate sensing, alerting, and deterrent mechanisms that safeguard wildlife and humans. Therefore, the PV modules require continuous monitoring and testing to maintain optimum condition and performance, thus ensuring the continuous operation of such systems.

The current-voltage (I-V) curve tracer is a common method for researchers to study the performance of solar panels by measuring electrical parameters such as voltage and current [5]. Solar cells and PV modules are characterized using several parameters, including the I-V curve, short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor, and efficiency [6]. The current is measured by applying a series of voltages and varying the load connected to the solar cell, which produces the I-V curve characteristic of the solar cells [7]. In this way, the I-V curve can extract the parameters to determine its current operating condition [8]. Various I-V curve tracer circuits with different load methods have been developed to identify the performance of rated solar panels. Initially, the resistive-load method using a potentiometer was the simplest method for a solar panel I-V curve tracer [9,10]. However, the potentiometer measurement took time because it was done manually, requiring changes to the resistance value [9]. Furthermore, the measurement of the I_{sc} was not accurate, and long measurement times cause variations in solar radiation and thermal conditions. Thus, this method had low accuracy and was limited to tracking continuously changing working and environmental conditions. Several resistors and additional switching relays were integrated to reduce the measurement time [11]. A rheostat paired with a 12-bit analog-to-digital converter (ADC) and a microcontroller was also used to automate the measurement process, resulting in increased data points on the curve [8].

Recent research has studied the performance of an I-V curve tracer with a Raspberry Pi microcontroller using two different approaches for a 520 W solar panel [12]. The first approach used a 300 Ω rheostat as the resistive load, with a slider that was manually changed from the lowest to the highest resistance value. The second approach used a 5.5 F 48.6 V supercapacitor as the capacitive load. This approach used high-voltage capacitors connected to active switches. The I-V curves can be measured automatically during the capacitor charging period, as the terminal voltage of the capacitors does not change abruptly and increases uniformly as the charge rises. For safety and accuracy, the voltage rating of the capacitor must be greater than the open-circuit voltage of the solar panel. The results showed that the capacitive-load method obtains a higher percentage of voltage measurement accuracy than the resistive load [13,14]. This result shows that the capacitive-load method can measure characteristic curves under uniform and changing environmental conditions while providing more reliable and accurate results than the resistive-load method.

The I-V curve tracer circuit using the transistor-load method has also been developed using an IRF740 MOSFET controlled by an Arduino microcontroller [15-17]. The design used a DC/DC booster to amplify a continuous signal generated by the microcontroller. Then, the signal was injected into the resistor-capacitor (RC) filter, which was connected in series to adjust the MOSFET control voltage (V_{gs}). This design produced fast and variable output from the solar panel. Thus, it was possible to reduce the effects of illuminance variations and temperature fluctuations caused by cloud movement or other weather conditions because all points of the I-V curve were measured under the same weather conditions over a very short time, while protecting the MOSFET from overheating. However, this method typically produces noise in its measurement due to transistor switching [8].

Furthermore, there was a study that compared the capacitive-load and transistor-load methods using an Arduino microcontroller to measure the I-V and power-voltage (P-V) curves of a solar panel under standard test conditions (STC) [18]. The measurement was performed with different resistance and capacitance values for both methods, and the curve obtained with the transistor-load method was found to be more accurate and faster than that obtained with the capacitive-load method. The characteristics and performance of different I-V curve tracing methods vary significantly depending on their operational principles and application needs [19]. Although many I-V curve tracer circuits have been reported, several limitations remain for remote and field-based PV validation. Commercial I-V tracers are accurate but costly, and laboratory setup tracer systems also require complex hardware, high-voltage components, or controlled test conditions. In addition, many reported studies focus on general PV characterization rather than on direct on-field validation for a practical low-power application such as a rural or conservation-based solar-powered system in a tropical environment. This creates a need for a low-cost, simple, and field-usable I-V tracer system that can provide sufficient information to select and validate solar PV panels for remote wildlife protection systems.

This paper presents the development of an Arduino-based I-V curve tracer circuit to investigate performance differences between polycrystalline and monocrystalline solar PV panels using a real-time data acquisition system for an elephant deterrent system. The system uses a capacitive-load method with an Arduino, a current sensor, a voltage sensor and a Microsoft Excel Data Streamer used for real-time data acquisition and recording. The comparative analysis focuses on short-circuit current, open-circuit voltage, maximum power, and daily power output. Fill factor is not used as a main performance metric due to the inherent current-measurement uncertainty in the low-cost circuit. The study is limited to solar PV panel validation for the deterrent power supply only. Furthermore, this study focuses on the development and field validation of a low-cost Arduino-based I-V curve tracer for selecting photovoltaic modules for a solar-powered elephant deterrent system. Unlike many studies that focus on laboratory setups or commercial instruments of PV characterization, this work evaluates monocrystalline and polycrystalline panels under actual tropical outdoor conditions.

2. METHODOLOGY

2.1 Block Diagram of I-V Curve Tracer System by Data Streamer

Figure 1 shows the block diagram for the I-V curve tracer system by Data Streamer. The I-V curve tracer system consists of an Arduino UNO board as the microcontroller, an INA219 current sensor, a F301-06 voltage sensor for I-V measurements, and the capacitive load with several additional components. The circuit is connected to the solar panel and Data Streamer. The Data Streamer tool in Microsoft Excel establishes serial communication with the Arduino board and displays the measured voltage, current and thus, calculated power in real time. The purpose of this system configuration is to provide a field measurement system that can be used without commercial instruments. The Arduino receives the voltage and current values, calculates the power and then, sends the data to Microsoft Excel through Data Streamer for plotting the I-V and P-V curves. The system was developed for small solar PV panels with low power rating used in the elephant deterrent system, where fast solar panel performance monitoring is required in off-grid locations.

2.1.1 Solar Photovoltaic Panels

Figure 2 shows the two types of solar panels, i.e., monocrystalline and polycrystalline, with a similar 10 W power rating. **Table 1** shows the power rating of solar panels under STC, representing the maximum power output a panel can produce under controlled laboratory conditions, typically a solar irradiance of 1000 W/m^2, a cell temperature of 25 °C and an air mass (AM) of 1.5. STC provides a standardized benchmark for comparing different solar panel models, but the actual field output is normally different from the STC values. In this work, both solar panels were tested in an outdoor location as part of the on-field elephant deterrent system. On-field output is affected by many factors, such as weather conditions, panel temperature, cloud shading, dust on the panel surface, tree shadows and the angle of sunlight. For this reason, two panels with the same 10 W power rating may give different current, voltage and power values during on-field operation. The comparison between the two types of PV technologies was therefore based on field measurements rather than only on the STC rating.

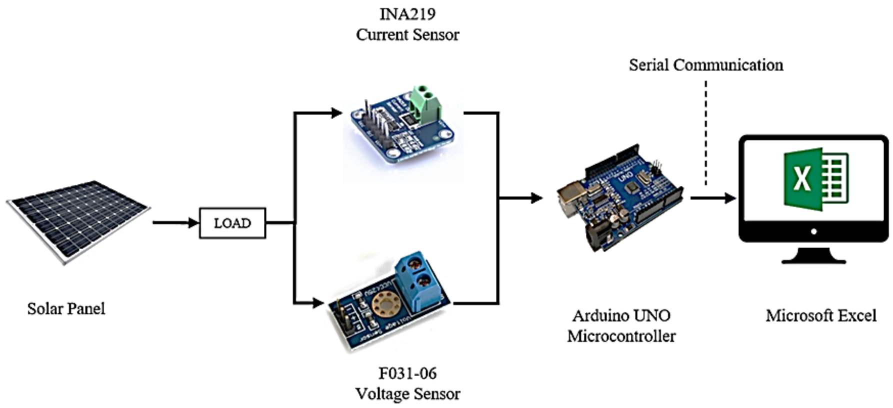


Figure 1. Block diagram of I-V curve tracer system by Data Streamer

Figure 2. Monocrystalline and polycrystalline solar panels

Table 1. A 10 W power rating of solar panels under standard test conditions (STC)

Parameter	Monocrystalline	Polycrystalline
Short circuit current, I_{sc} [A]	0.63	0.62
Open circuit voltage, V_{oc} [V]	21.24	21.50
Maximum power current, I_{mp} [A]	0.58	0.58
Maximum power voltage, V_{mp} [V]	17.50	18.00

2.1.2 Current Sensor

Figure 3 shows the INA219 current sensor module used for current measurement in the tracer circuit. The sensor was placed in series with the solar panel and the capacitive load, where the solar panel current is measured during the capacitor charging condition. The INA219 module used in this system has a 0.1 W shunt resistor and communicates with the Arduino UNO through the inter-integrated circuit (I^2C) connection. The module can operate from the 5 V voltage supply provided by the Arduino board and can measure the high-side current of the PV module. This is suitable for the 10 W solar panels used in the experiment because the expected current is below 1 A. The current data from the INA219 was sent to the Arduino and then displayed in Microsoft Excel through Data Streamer. For on-field application, the INA219 was selected because it is low-cost, easy to connect to Arduino and suitable for low-power PV modules [20]. However, the current accuracy is lower than that of commercial equipment, especially during the fast capacitor charging transient. Therefore, the current measurement was validated against a digital multimeter (Fluke 175) before the field test, and the uncertainty is considered when interpreting the I-V curve results.

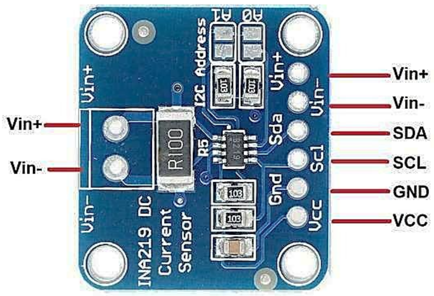


Figure 3. INA219 shunt current sensor module

2.1.3 Voltage Sensor

Figure 4 shows the F301-06 voltage sensor, connected in parallel with the capacitive load to measure the voltage output of the solar panel. The sensor operates in a voltage-divider configuration with 30 kΩ and 7.5 kΩ resistors in series. This configuration reduces the input voltage by a factor of 5, converting the PV output range of 0-25 V into a measurable range of 0-5 V. This configuration ensures compatibility with the Arduino, which has an analogue input restricted to 5 V [3]. This sensor enables monitoring the solar panel voltage while ensuring that the Arduino operates within safe input limits. As the capacitor charged, the voltage increased from near 0 V towards the open-circuit voltage of the solar panel. The measured voltage was read by the Arduino analogue input and used with the current measurement to calculate the power.

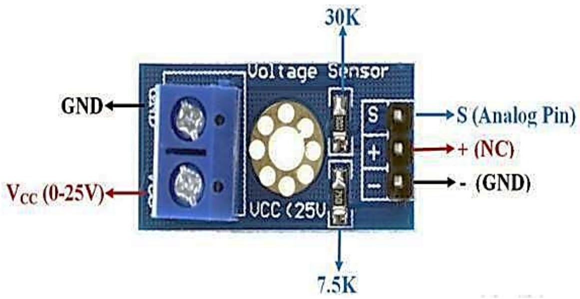


Figure 4. F301-06 voltage sensor module

2.1.4 Capacitive Load

The capacitive-load method was used to acquire the I-V characteristics of the solar panels due to its advantages, including low noise, low power consumption, simple circuitry and the ability to automatically capture the curve in a short time. This approach involves an initially uncharged capacitor, which draws a high current when connected to the solar panel. During capacitor charging, the increasing voltage across the capacitor opposes the current flow. Hence, this condition allows the I-V curve of the solar panel to be mapped from the short-circuit region towards the open-circuit region. The sweep occurs over a short time (~ms), which helps reduce the effect of irradiance changes during one measurement. In this work, a 30 ms sweep was used as the target charging time for the I-V curve measurement. The capacitance value (*C*) for the load was determined using **Eq. 1** [21]:

$$C = 0.5t\frac{I_{sc}}{V_{oc}} \tag{1}$$

where t is the charging/discharging time, assumed to be 30 ms. The capacitance values for the monocrystalline panel and polycrystalline panel were 445 µF and 470 µF, respectively. Based on these calculations, a 470 µF capacitor rated for 25 V was selected for the capacitive load setup.

A discharge path was also included so that the capacitor can be discharged before the next measurement. This is important because a partly charged capacitor will not start the next sweep from the short-circuit region. In the circuit, the discharge path used a switch and a 5 kΩ resistor. The capacitor voltage (V_{cap}) was checked before each sweep and was allowed to drop below 0.1 V before the next measurement was started. Furthermore, the selected capacitor voltage rating is higher than the open-circuit voltage of both solar panels. Short wiring was used in the capacitive load circuit to reduce additional resistance and inductance during the fast-charging period. This is important because the spike in inrush current at the beginning of capacitor charging process can contribute to current measurement errors.

2.1.5 Data Streamer

Microsoft Excel was used to record and plot data acquired from the tracer circuit. The Data Streamer tool creates a serial connection between the Arduino board and an Excel spreadsheet, allowing real-time monitoring of electrical parameters. **Figure 5** shows the workspace of the Data Streamer. Before measurement, the user selects "Connect a Device" and identifies the COM port linked to the Arduino board. Graph templates for I-V and P-V curves are incorporated into the worksheet prior to data acquisition. When "Start Data" is clicked, the measured parameters, including voltage, current and power are displayed in the workspace. As the data stream continues, the curve plots are updated automatically. The "Record Data" function is used to save measurement values to a file. The "Stop Data" is used to end the measurement process. Meanwhile, the "Reset Data" function is used to clear the workspace for subsequent measurements under new test conditions. In this study, Data Streamer was selected because it is useful for on-field data acquisition, allowing the user to connect the tracer circuit directly to a laptop and view I-V and P-V curves in an Excel worksheet without installing additional software.

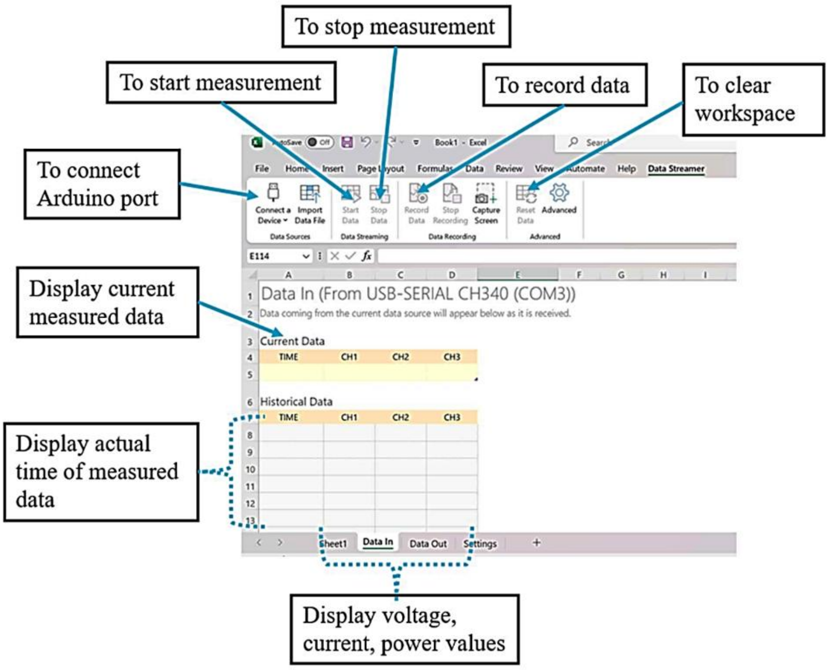


Figure 5. Workspace of Data Streamer in Microsoft Excel

2.2 System Flowchart

Figure 6 shows the flowchart for the measurement process using the developed Arduino-based I-V curve tracer system to extract solar PV parameters using the capacitive-load method and to monitor solar panel performance. The process begins by setting up the Arduino-based tracer circuit and the establishment of serial communication with the computer, which provides 5 V to the system. The Data Streamer tool in Microsoft Excel is then used to receive the sensor data from the Arduino. The system conducts a self-check to confirm sensor stability. The supply voltage is checked to ensure it exceeds 4.8

V, while the current reading is observed to confirm that variation remains within ±0.01 A before starting the measurement sweep. Before starting the measurement, confirm that the capacitor is fully discharged (V_{cap} < 0.1 V). Otherwise, the discharge path is engaged by the switch and 5 kΩ resistor. After the capacitor is discharged, it is connected to the solar panel output. The capacitor then charges rapidly and sweeps the operating range of the solar panel. The voltage increases from near 0 V to the open-circuit voltage, while the current decreases from near short-circuit current towards 0 A. The INA219 current sensor and F301-06 voltage sensor record the current and voltage during this charging period. The sweep ends when the capacitor voltage approaches the open-circuit voltage and the current approaches zero. The data are transmitted to the computer, where the I-V and P-V curves are calculated and displayed in real time. The results are then saved for comparison between the monocrystalline and polycrystalline solar panels. In addition, a delay was included in the Arduino algorithm to stabilize the serial output for Excel logging. This delay affected only the display and recording intervals in Excel and did not alter the actual capacitor charging response during the sweep. After each sweep, the capacitor was discharged before the next measurement was taken.

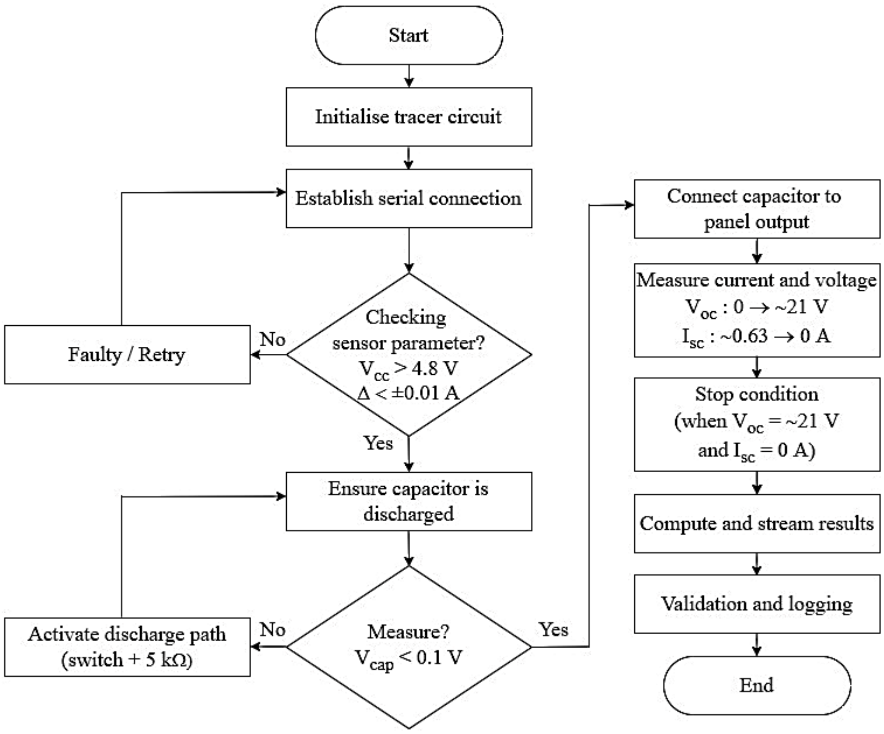


Figure 6. Flowchart for the measurement process using an Arduino-based I-V curve tracer system

2.3 Hardware and Software Integration

Figure 7 shows the system integration of the real-time I-V curve monitoring system for solar PV panels. The setup configuration consists of an Arduino UNO, current and voltage sensors, and a capacitive-load circuit. The solar PV panel is connected in series connection with the capacitor load circuit for sweeping the I-V curve. A potentiometer was also connected in series to adjust the charging rate of the capacitor. During the measurement process, a resistance value was obtained by manually adjusting the potentiometer, thereby regulating the charging time, which controls the voltage and current sweep. In addition, a discharge circuit consisting of a switch and a potentiometer was included to provide a discharge path and release the storage charge after each measurement cycle. The INA219 current sensor was placed in series with the solar PV panel and the capacitor load to measure the output current, while the F301-06 voltage sensor was placed in parallel with the capacitor load to measure the output voltage. The Arduino microcontroller processes the measured output voltage and current values and computes the corresponding power in real time. The measured and computed values are also displayed on an LCD as an indicator to the user. At the same time, the data are sent to a computer through serial communication for storage and I-V curve plotting. Thus, the hardware and software integration is suitable for evaluating solar panel performance under sunlight because the sweep can be completed within a short period, reducing the effect of irradiance variation during measurement. **Figure 8** shows the actual experimental setup used at the on-field site for real-time I-V curve measurement test.

For each test day, the same I-V tracer circuit was used for both solar panels while maintaining the consistency of the sensors, wiring, capacitive load, and Arduino operation. Since the measurements were conducted under on-field conditions, variations in solar irradiance and panel temperature during the testing period may have introduced an uncertainty of about ±5–10%. Sequential testing allows a more controlled and detailed comparison of solar panel performance [22,23]. In addition, measuring the electrical variables under selected operating conditions can provide useful information on solar panel efficiency, reliability and possible failure behavior, making it a supporting method for solar panel evaluation [24,25]. All measurements were carried out within a consistent daylight period and under similar conditions. The irradiance level was checked before each test, and both solar panels were positioned at the same location and orientation. Before the measurements, the readings from the voltage and current sensors were compared with a digital multimeter (Fluke 175). This validation was performed to check the accuracy of the data-acquisition circuit. The performance analysis in this testing focuses on the I-V curve shape, open-circuit voltage, short-circuit current and maximum power trends. The fill factor is not considered as a part of the performance indicator because it is more affected by the sensitivity of current measurement errors.

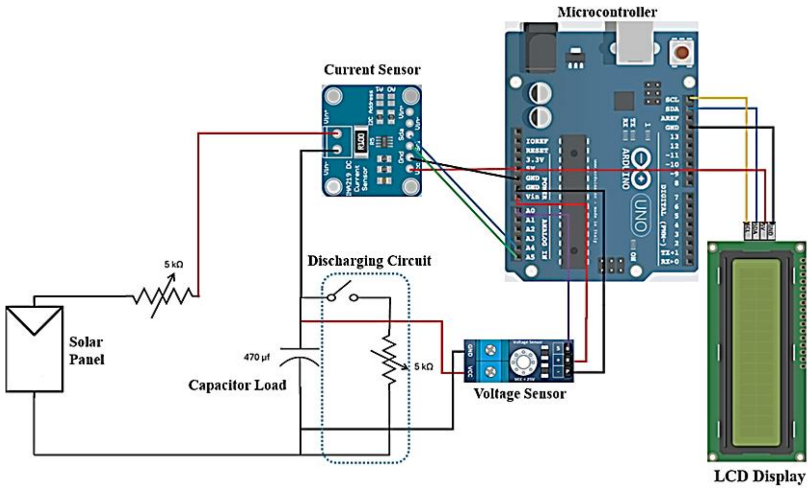


Figure 7. Circuit diagram of the real-time I-V curve monitoring system using Arduino, voltage and current sensors, and capacitive-load configuration

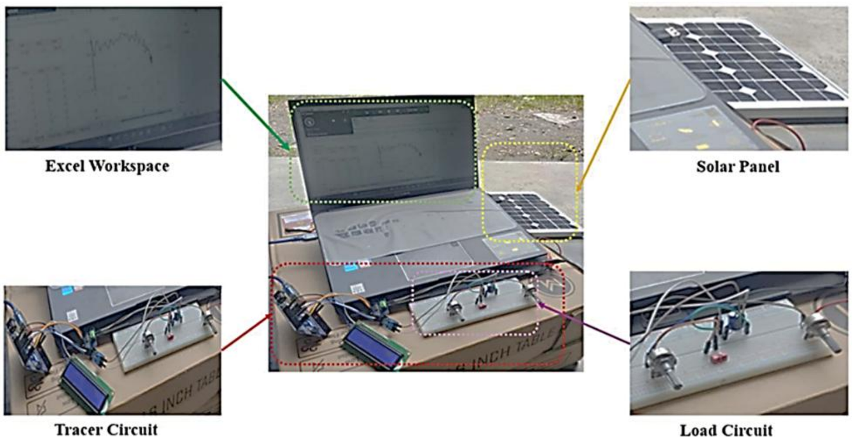


Figure 8. Real experimental setup for real-time I-V curve monitoring system

2.4 Field Testing Procedure

The on-field test was conducted from 23 May 2024 to 3 June 2024 for 10 days, to represent the operating environment of the solar-powered elephant deterrent system. During the 10-day test period, the ambient temperature ranged up to 33 °C, while the measured irradiance ranged from 789 W/m² to 1270 W/m². These values align with expected clear-sky irradiance levels in tropical environments, with fluctuations attributed to transient cloud cover and diurnal effects [26]. Both 10 W monocrystalline and 10 W polycrystalline panels were placed at the same test location. The panels were positioned with the same orientation and tilt angle during measurement. The results were then compared to determine panel type performance for supplying the low-power elephant deterrent system under tropical field conditions.

3. RESULTS AND ANALYSIS

3.1 Validation of Real-Time I-V Tracer Measurements

Table 2 presents a comparison of readings between the measured current and voltage values by the I-V curve tracer circuit and digital multimeters for both monocrystalline and polycrystalline solar panels. The Voc measured with the tracer was close to the multimeter readings for both panel types. The voltage error ranged from 0.65% to 0.81% for the polycrystalline panel. In contrast, the monocrystalline panel recorded an error range of 0.74% to 0.79%. The average voltage error was about ±0.72%, which indicates that the voltage sensor operated in good condition. However, a higher deviation was observed for the Isc. In the monocrystalline panel test, the tracer circuit measured current between 0.5 and 0.8 A, whereas the multimeter readings ranged from 0.6 to 0.7 A. This produced an error range of 14.29% to 16.67%. For the polycrystalline panel, the error ranged from 0% to 14.29%. The mean current error was approximately 8.18%, with the highest error reaching 16.67%. This current error is higher than the voltage error because the current measurement was taken during a fast capacitor-charging transient rather than during a steady-state load condition.

Table 2. A comparison of readings for the solar panel's parameters

Solar Panels	Parameter	Tracer Circuit	Multimeter	% Error
Monocrystalline	I_{sc} [A]	0.5 – 0.8	0.6 – 0.7	14.29 – 16.67
	V_{oc} [V]	18.72 – 18.74	18.87 – 18.88	0.74 – 0.79
Polycrystalline	I_{sc} [A]	0.5 – 0.7	0.6 – 0.7	0 – 14.29
	V_{oc} [V]	18.37 – 18.41	18.52 – 18.53	0.65 – 0.81

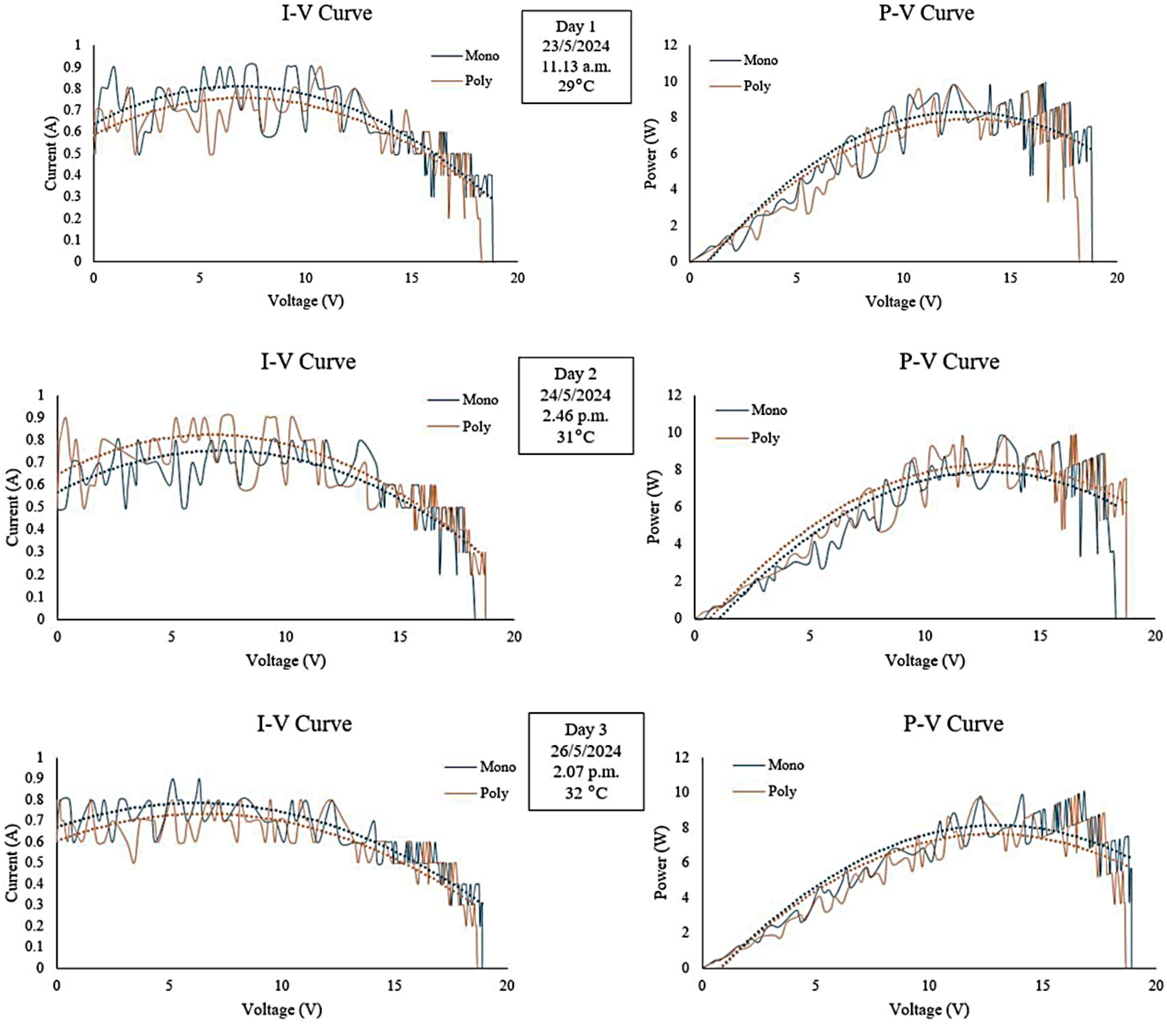
This error is mainly caused by the INA219 shunt response during the short capacitor-charging period, where inrush current, wiring resistance, fast sweep timing and parasitic inductance can affect the measurement. This effect is more visible in the current measurement because the current changes rapidly at the start of the sweep.

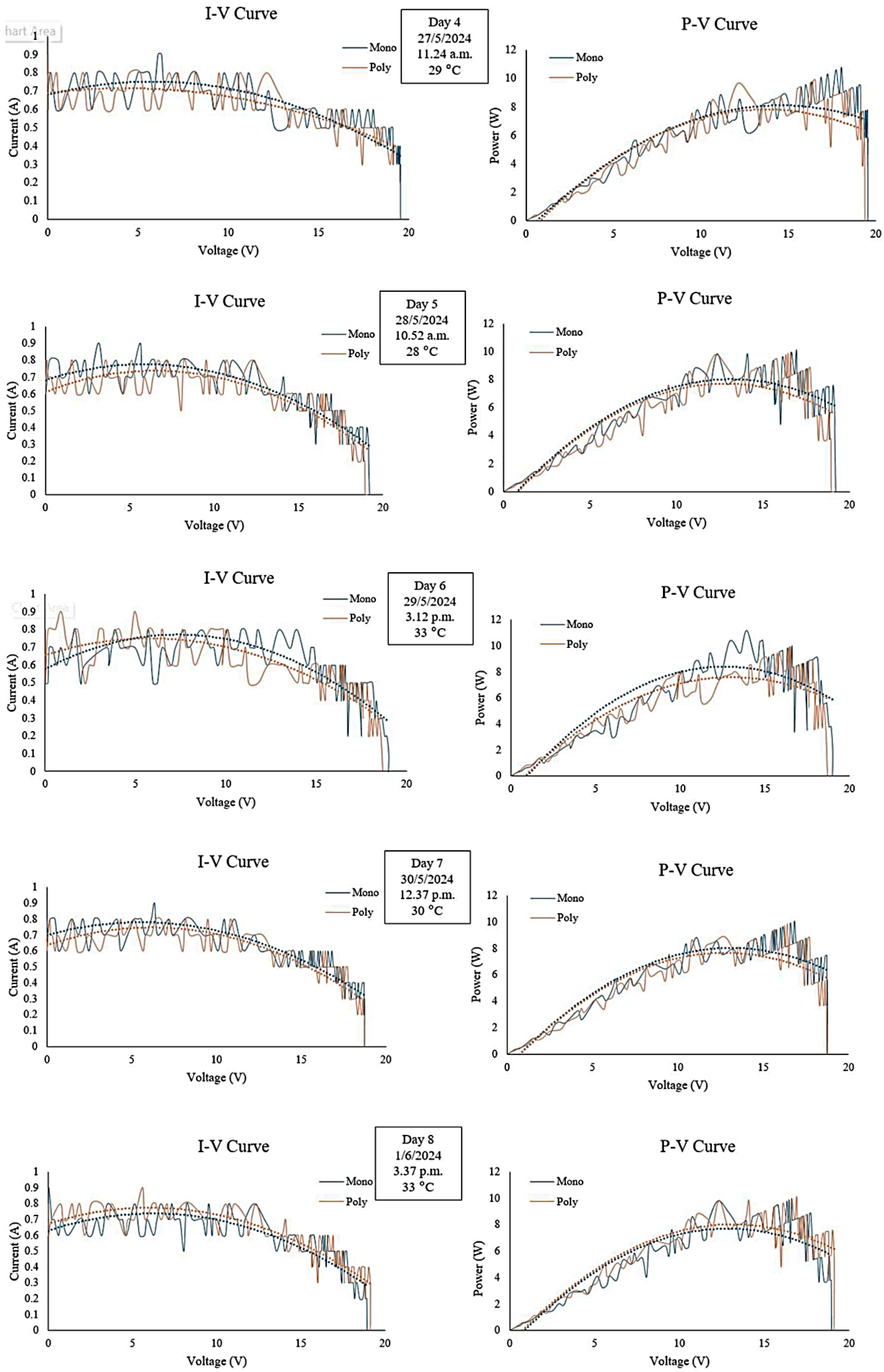
3.2 Performance Comparison of Monocrystalline and Polycrystalline Solar Panels

Figure 9 shows the 10-day comparison of I-V and P-V curve measurements for monocrystalline and polycrystalline solar panels. The solid lines represent the raw real-time measurements captured by the tracer system, while the dashed lines represent the smoothed values. Data smoothing was applied to reduce small fluctuations caused by sensor noise and short-term changes in irradiance during data acquisition. The monocrystalline solar panel produced a higher maximum power output (P_{max}) on 8 of the 10 test days. This result indicates that the monocrystalline module had a more consistent field advantage under the tested on-field conditions. A binomial test was applied to the 8-out-of-10 result, assuming an equal probability that either solar panel would perform better on any given day. The result showed $p = 0.0274$, which indicates that the observed advantage of the monocrystalline panel was statistically significant at the 5% level for this 10-day dataset.

Generally, the I-V and P-V curves of the monocrystalline panel were smoother and showed higher current at comparable voltage levels, resulting in a higher and more stable power region in the P-V curves. In contrast, the polycrystalline panel showed more irregular curve shapes on several days, with visible fluctuations. However, the polycrystalline panel did not perform poorly under all test days. On cloudy or lower-irradiance days such as Day 2 and Day 8, the polycrystalline panel slightly exceeded the monocrystalline panel output. This behavior may be related to the spectral response of polycrystalline cells, which can sometimes perform better under diffuse light conditions. Therefore, the results do not suggest that polycrystalline panels are unsuitable for on-field use. Rather, the measured trend shows that the monocrystalline panel gave better overall power output across the 10-day test period.

Moreover, under on-field conditions, the PV module temperature is typically higher than the ambient air temperature, often by 10-20 °C, depending on wind speed, mounting conditions, and irradiance [27]. Increased cell temperature directly affects the open-circuit voltage and overall module efficiency [28]. Since module temperature was not measured directly, the results are therefore discussed mainly as field output under measured ambient temperature and irradiance conditions. In addition, the time difference between the two readings may introduce approximately ±5-10% uncertainty due to changes in irradiance and temperature. This limitation was reduced by keeping the panel location, orientation, and test period consistent.




I-V Curve
Day 4
27/5/2024
11.24 a.m.
29 °C
Mono
Poly
Current (A)
Voltage (V)
P-V Curve
Power (W)
I-V Curve
Day 5
28/5/2024
10.52 a.m.
28 °C
P-V Curve
I-V Curve
Day 6
29/5/2024
3.12 p.m.
33 °C
P-V Curve
I-V Curve
Day 7
30/5/2024
12.37 p.m.
30 °C
P-V Curve
I-V Curve
Day 8
1/6/2024
3.37 p.m.
33 °C
P-V Curve

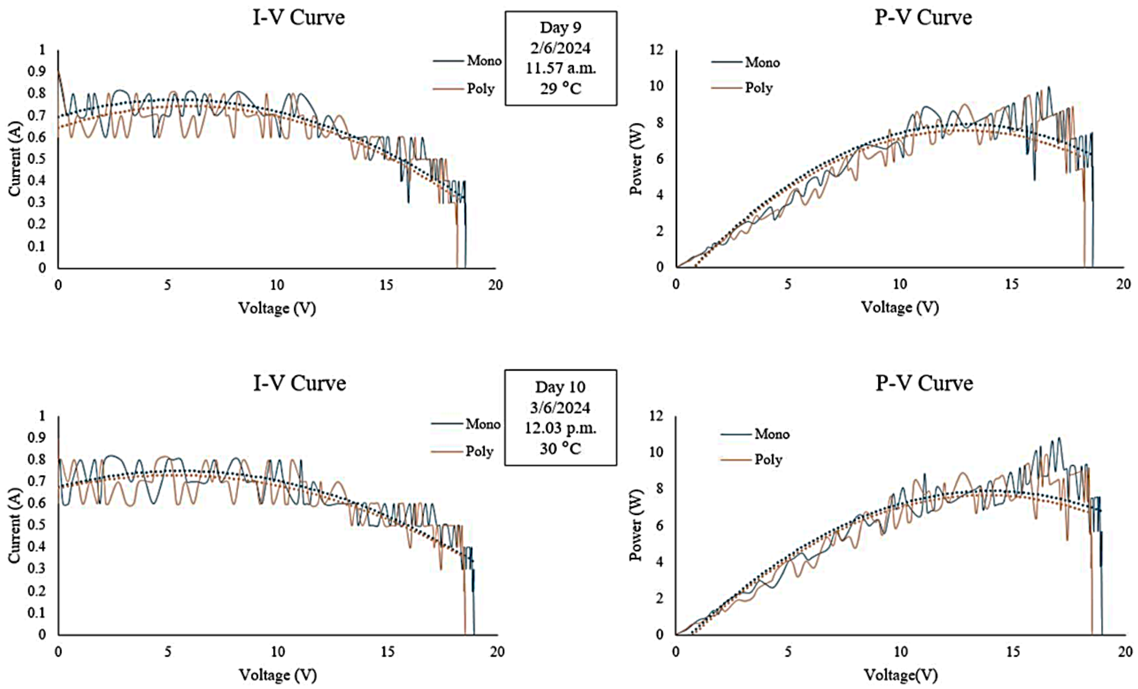


Figure 9. 10-Day comparison of I-V and P-V curve measurements for monocrystalline and polycrystalline solar panels under on-field conditions

3.3 Maximum Power Output Trend Analysis

Figure 10 shows the P_{max} for the monocrystalline and polycrystalline solar panels over the 10 days. The monocrystalline panel produced higher P_{max} on most days, while the polycrystalline panel showed higher P_{max} on Day 2 and Day 8. The highest P_{max} at 10.8 W was recorded by the monocrystalline panel on Day 4, while the polycrystalline panel reached about 10.2 W on the same day. The largest visible difference also occurred on Day 4, where the monocrystalline panel produced 5.8-6.0% higher power output. These values were slightly higher than the nominal 10 W power rating because the on-field irradiance exceeded 1000 W/m^2 on certain days and reached up to 1270 W/m^2. For most of the testing period, the power difference between the two panels was relatively small, which indicates that the overall output power remained consistent. However, on Day 8, the polycrystalline panel produced a higher power output than the monocrystalline panel. This result indicates that the polycrystalline panel operates effectively during cloudy or diffuse-light conditions. Furthermore, based on the 10-day period, the monocrystalline panel delivered a higher maximum power output to the power supply of the remote deterrent unit. For remote and off-grid systems such as virtual fencing and wildlife deterrent applications, the field performance consistency is more important than laboratory-scale values. The solar PV panels must supply adequate energy under changing outdoor sunlight conditions throughout the day [29,30]. From the 10-day on-field testing, the monocrystalline panel indicates a suitable option for continuous energy harvesting. The polycrystalline panel remains a practical alternative, particularly under cloudy or diffuse-light conditions.

3.4 Comparison Analysis and Applications

Table 3 presents a comparison of the measured values of maximum power, current and voltage for the monocrystalline and polycrystalline panels with their respective STC specifications. For the monocrystalline panel, the highest measured P_{max} was 10.123 W, which was obtained at a current of 0.666 A and a voltage of 18.897 V. When compared with the respective STC rating, the power output difference was small, with a deviation of –0.26%. However, the measured current was 5.71% higher, while the measured voltage was 11.03% lower than the STC-rated value. Meanwhile, for the polycrystalline panel, the measured P_{max} was lower at 9.931 W, with respect to the current of 0.670 A and voltage of 18.729 V. The respective deviations from the STC rating values were –2.26% for power,

+8.06% for current and –12.89% for voltage. The increase in current and reduction in voltage observed for both panels are attributed to outdoor operating conditions, where irradiance levels and PV module temperature are different from STC [31,32].

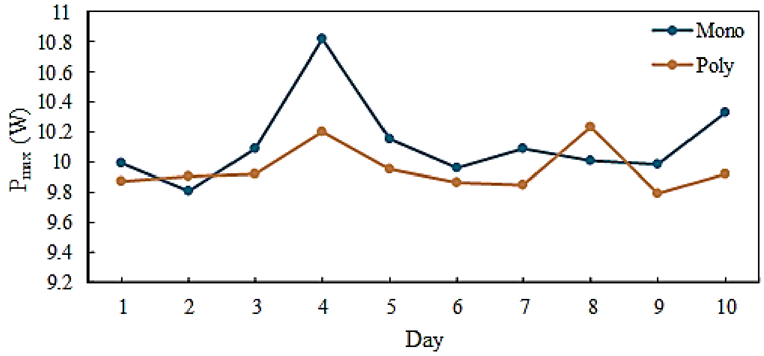


Figure 10. Daily maximum power output (P_{max}) for monocrystalline and polycrystalline solar panels over 10 days

Table 3. Comparison of maximum power, current, and voltage for monocrystalline and polycrystalline solar panels under on-field and STC

Solar Panel Type	P_{max} [W]	Relative Error (%)	I_{sc} [A]	Relative Error (%)	V_{oc} [V]	Relative Error (%)
Monocrystalline	10.123	-0.26	0.666	5.71	18.897	-11.03
STC Monocrystalline	10.150	-	0.630	-	21.240	-
Polycrystalline	9.931	-2.26	0.670	8.06	18.729	-12.89
STC Polycrystalline	10.150	-	0.620	-	21.500	-

Analysis of the I-V and P-V curves over 10 days provides practical guidance in selecting a PV panel for the off-grid automated elephant deterrent system. In this work, the two solar panels were assessed not only based on their rated specifications, but also on how well they may sustain usable output under actual on-field conditions. This is important for remote or isolated locations, where grid electricity is often unavailable and solar energy becomes the most practical power source. The Arduino-based I-V tracer with a capacitive load allows direct voltage, current, and power measurements at the installation site. Such on-field assessment is useful for off-grid deterrent units, since unstable solar PV output may reduce the reliability of battery charging and affect the long-term operation of the system. For the elephant deterrent system, the measured solar PV output is sufficient to support the required operating load. An Arduino-based deterrent unit including sensors, amplifier module and speaker, consumes approximately 0.7-2 W in standby mode and 3-12 W during active sound emission. Since the speaker operates intermittently, the average daily load is expected to be much lower than the peak demand. Under this operating condition, the tested solar PV module can support a low-power deterrent system. However, a larger solar PV power rating may improve reliability during cloudy periods or frequent activations. The result is important because deterrent systems are often installed in remote agricultural or conservation borders, where grid supply is unavailable and maintenance access is limited [33].

4. CONCLUSION

This work addressed the need for a low-cost, practical method to validate photovoltaic performance for powering remote, off-grid systems. The developed Arduino-based I-V curve tracer captured real-time current-voltage and power-voltage characteristics via the Microsoft Excel Data Streamer, which enables field-based comparison of monocrystalline and polycrystalline photovoltaic panels without relying on expensive commercial I-V tracers. Over the 10-day field test, the monocrystalline panel showed better performance on 8 out of 10 days and achieved a maximum power output of 10.8 W. The measured PV output was higher than the estimated maximum average load of 2 W required by the elephant deterrent unit, which indicates that the tested panel can provide sufficient energy surplus for battery charging and continuous low-power operation. This work supports the use of solar PV power in wildlife deterrent applications, particularly in conservation fields where off-grid operation is required. Future work should improve the accuracy of current measurement, conduct simultaneous testing of the panels and validate the complete deterrent system over a longer operating period.

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6. AI USAGE DECLARATION

Authors would like to declare that Grammarly was used as a language assistance tool during the revision process. Specifically, the tool was used to assist with grammar, spelling and punctuation to improve the clarity of the manuscript. All experimental work, data collection, technical content and analysis, interpretation and conclusions presented in the manuscript are the authors' own work. The authors take full responsibility for the accuracy, originality and integrity of the manuscript.

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