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Measuring Photosynthetically Active Radiation with the Arduino Platform

Medida da Radiação Fotossinteticamente Ativa com a Plataforma Arduino

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Abstract
Photosynthetically Active Radiation (PAR) encompasses the wavelengths between 400 and 700 nm that are used by plants for photosynthesis, converting solar energy into chemical energy. This process is essential for the growth and development of plants. Given the importance of this variable, the study had the objective evaluated the feasibility of using Arduino as an alternative for the PAR measurement. The measurements were taken using amorphous silicon photodiodes (ASF) covered with an acrylic diffuser. The PAR measurements with the ASFs connected to the Arduino and the CR1000 were calibrated using a Quantum sensor from Li-Cor. The hardware used was the Arduino Mega 2560, a datalogger shield, and an analog to digital converter (ADC). The ASF was connected to the Arduino through an ADC for amplifying the generated voltage. Each ASF was also connected to an AM25T multiplexer and the Campbell Scientific® CR1000 datalogger. The data obtained were analyzed using linear regression with SAS. In calibrations performed with the CR1000, the root mean square error (RMSE) ranged from 16.2 to 48.72 µmol m^{-2} s^{-1} with a coefficient of variation (CV) from 1.91 to 5.76%. With the Arduino, the RMSE values obtained ranged from 5.28 to 35.30 µmol m^{-2} s^{-1},

and the CV was between 0.53 and 3.32%. The similarity in error variability indicates that Arduino is a alternative for measuring PAR.

Keywords: Precision. Datalogger. Calibration. Variability. Comparison.

Resumo
A Radiação Fotossinteticamente Ativa (RFA) abrange os comprimentos de onda entre 400 e 700 nm que são usados pelas plantas na fotossíntese, convertendo energia solar em energia química. Esse processo é essencial para o crescimento e desenvolvimento das plantas. Diante da importância dessa variável, o estudo teve o objetivo de avaliar a viabilidade do uso do Arduino como alternativa na medida da RFA. As medidas foram realizadas com fotocélulas de silício amorfo (FSA), cobertas com difusor de acrílico. As medições da RFA com as FSA conectadas ao Arduino e ao CR1000 foram calibradas usando um sensor Quantum da Li-Cor. O hardware utilizado foi o Arduino Mega 2560, um datalogger Shield e um conversor analógico digital (CAD). A FSA foi ligada no Arduino por meio de um CAD para a amplificação da tensão gerada. Cada FSA também foi conectada ao multiplexador AM25T e ao datalogger CR1000 da Campbell Scientific®. Os dados obtidos foram analisados por regressão linear usando o SAS. Nas calibrações efetuadas com o CR1000 a raiz quadrada média do erro (RQME) variou de 16,2 a 48,72 μmol m^{-2} s^{-1} com coeficiente de variação (CV) de 1,91 a 5,76%. Com o Arduino, os valores de RQME obtidos variaram entre 5,28 e 35,30 μmol m^{-2} s^{-1} e o CV de 0,53 a 3,32%. A similaridade na variabilidade dos erros indica que o Arduino é uma alternativa para medira RFA.

Palavras-chave: Precisão. Datalogger. Calibração. Variabilidade. Comparação.

1 Introduction

Solar radiation measurements are essential for optimizing the performance of photovoltaic generation systems (Domingos; Monteiro; Boaventura, 2020) as well as for conducting experiments in agricultural crop cultivation (Bergamaschi *et al.*, 2010; Cardoso *et al.*, 2010; Dalmago *et al.*, 2018; Lemainski *et al.*, 2023). Understanding the solar energy potential of a specific region is of utmost importance to ensure the efficient utilization of this resource. Achieving this objective requires the use of the most suitable and commercially available solar radiation measurement instruments (Shibuya; Lei, 2022).

The assessment of photosynthetically active radiation (PAR) represents a fraction of global solar radiation and is particularly significant due to its direct influence on crop productivity and biomass production (Pereira; Gomes, 2015). PAR encompasses the visible spectral range (0.40 to 0.70 μm) and is responsible for stimulating chlorophyll molecules, thereby providing the necessary energy for photosynthesis (Steidle Neto *et al.*, 2006). To achieve accurate measurements, each sensor must be calibrated against a reference sensor that is sensitive to the same spectral range (400 to 700 nm), ensuring both sensors are exposed to identical conditions (Solems, 2011).

The intensity and quality of PAR are strongly influenced by several factors, including geographical location, seasonality, and prevailing meteorological conditions. Spatial and temporal variations in PAR are critical for determining the energy available for photosynthesis, shaping not only local vegetation patterns but also influencing plant community dynamics, species composition, and canopy architecture in forest ecosystems (Proutsos *et al.*, 2022). This highlights the need for continuous PAR measurements rather than relying solely on fixed relationships between PAR and global solar radiation.

Technological advancements and increased accessibility to electronic devices have significantly accelerated research and the development of equipment across various scientific disciplines (Kumar *et al*., 2021). To democratize the use of microcontrollers, prototyping platforms such as Arduino have emerged, gaining widespread adoption in experimental and practical projects. These platforms demonstrate significant potential for optimizing production processes (Marques Filho; Rodrigues; Ponte, 2021). Arduino is an open-source platform that integrates hardware and software, consolidating the entire system into a single board (Albino, 2014), thereby facilitating the development of electronic projects in an accessible and intuitive manner.

An Arduino board can read data from various types of sensors and control multiple devices and actuators, enabling the construction of interactive and automated systems with ease (Bachinski; Stefanello, 2014). PAR measurements can be conducted using high-precision Quantum sensors, which, however, entail substantially high instrument costs (Alves *et al*., 2020).

Amorphous silicon photodiodes (ASP) can also be employed for PAR measurements (Chartier *et al*., 1989). Amorphous silicon is a non-crystalline form of silicon, characterized by the absence of an ordered crystalline structure. This type of silicon is widely used in photodiodes due to its distinct properties, such as ease of fabrication and relatively low cost. According to the ASP manufacturer's manual, the required electrical voltage to generate 1000 μmol m^{-2} s^{-1} is approximately 30 mV (Solems, 2011), necessitating a measurement system with considerable sensitivity and precision. The Arduino platform can be utilized in this context through an analog-to-digital converter sensitive within this measurement range. Barnard, Findley, and Csavina (2014) have previously demonstrated that PAR measurements using Quantum sensors can be conducted with Arduino. However, the use of ASP for PAR measurement with Arduino still requires further evaluation.

Thus, the objective of this study was to assess the technical feasibility of the Arduino platform for photosynthetically active radiation measurements using amorphous silicon photodiodes.

2 Material and Methods

The study was conducted in the experimental area of the Department of Plant Science at the Universidade Federal de Santa Maria, located in Santa Maria, RS, Brazil, at a latitude of 29º 41' S, longitude of 53º 48' W, and an altitude of 95 meters. The site features wide open horizons to minimize the effects of diffuse PAR and includes a conventional weather station operated by the National Institute of Meteorology.

Initial evaluations for each ASP (Amorphous Silicon Photodiode) were performed using a CR1000 datalogger combined with an AM 16/32B multiplexer on July 21, 2023. With the Arduino system, calibrations were conducted on August 29, 2023, and August 14, 2024. These dates were selected due to favorable PAR availability and minimal cloud cover. To prevent data variability caused by temporal discrepancies in minute-by-minute averaging—since the systems operate independently—periods with minor cloud presence or data recording failures were excluded.

PAR measurements were carried out using four replicates of amorphous silicon photodiodes (ASP) installed in support and shelter structures identified as Black Prototype (PP03), Metal Prototype (PM06), and White Prototype (PB02). Each ASP was connected to the Arduino via a 16-bit analog-to-digital converter (ADS1115), which enabled voltage amplification. The applied amplification factors were 2/3X, 1X, and 16X, allowing for potential improvements in resolution and sensitivity to voltage variations. Each ASP was manufactured by Solems using silicon films with a P-I-N junction structure (Borges, 2021). To ensure uniform light dispersion, the ASP in each prototype was covered with acrylic diffusers.

Reference PAR measurements were obtained using two Quantum sensors (serial numbers Q25755 and Q36600) connected to a LI-1400 datalogger from Li-Cor. Data acquisition and processing were performed using an Arduino Mega 2560 board equipped with a datalogger shield, enabling the amplification of the voltage generated by the photodiodes. The Arduino Mega 2560 is a microcontroller board that utilizes the ATmega2560 as its main chip, featuring 54 digital input/output pins (15 of which can be configured as PWM outputs) and 16 analog inputs.

Measurements were recorded every second and stored as one-minute averages on SD cards in the Arduino, as well as in the LI-1400 datalogger. For calibration purposes, the Quantum sensors (serial numbers Q25755 and Q36600) were used as the standard reference for PAR. The ASP sensors that exhibited the best performance in previous calibrations with the CR1000 datalogger were integrated into the Arduino system to ensure accuracy, comparability, and data reliability.

Following data collection, the dataset was subjected to linear regression analysis (Storck *et al.*, 2000) using the web-based version of SAS software. This allowed for the calculation of the calibration coefficient (CC), root mean square error (RMSE), and coefficient of variation (CV). These parameters facilitated an effective comparison between the calibration results obtained with the Arduino and those obtained with the CR1000 datalogger.

Data analysis was conducted in two phases. In the first phase, the calibration coefficient (CC) was determined using a first-degree linear equation without an intercept. In this case, the CC represents the slope of the linear equation, where the intercept was set to zero. The mean PAR values from the two Quantum sensors were considered the dependent variable, while the voltage measured by the ASP was treated as the independent variable for all measurement systems.

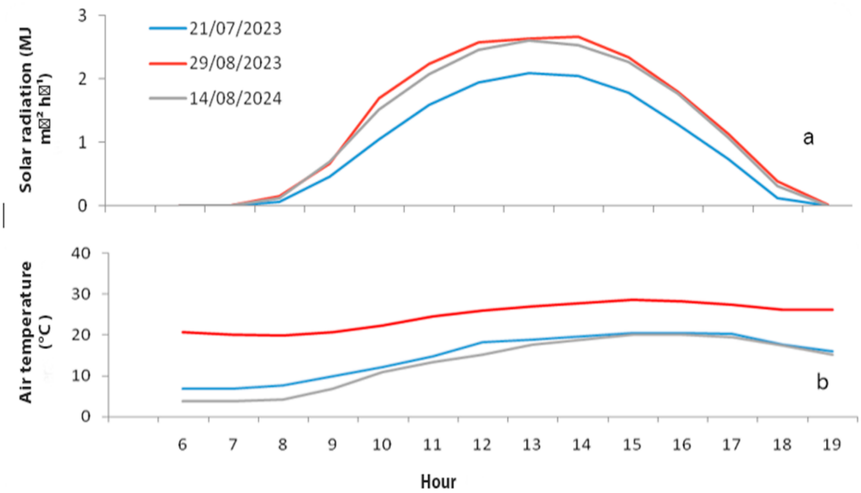
In the second phase, to account for potential differences in the response magnitudes between PAR and the voltage readings from the various systems, data normalization was performed. Each

PAR and voltage observation was divided by the maximum value recorded for that day. This normalization yielded values ranging from zero to one for each measurement system, facilitating error comparison in the regression analysis. For both phases, the analysis was conducted using the PROC REG procedure, one of the most robust statistical tools available in SAS for performing linear regression.

3 Results and Discussion

The maximum global solar radiation levels were approximately 2.08, 2.60, and 2.66 MJ m^{-2} h^{-1} on July 21, August 14, and August 29, respectively, indicating days with high radiation availability (Figure 1). The recorded maximum mean air temperature was 28.6°C, 20.1°C, and 20.6°C on July 21, August 14, and August 29, respectively (INMET, 2023). These conditions represent favorable environmental settings during the calibration process, particularly similar to the high solar radiation availability days selected in the analyses conducted by Alves *et al*. (2020) and Barnard, Findley, and Csavina (2014).

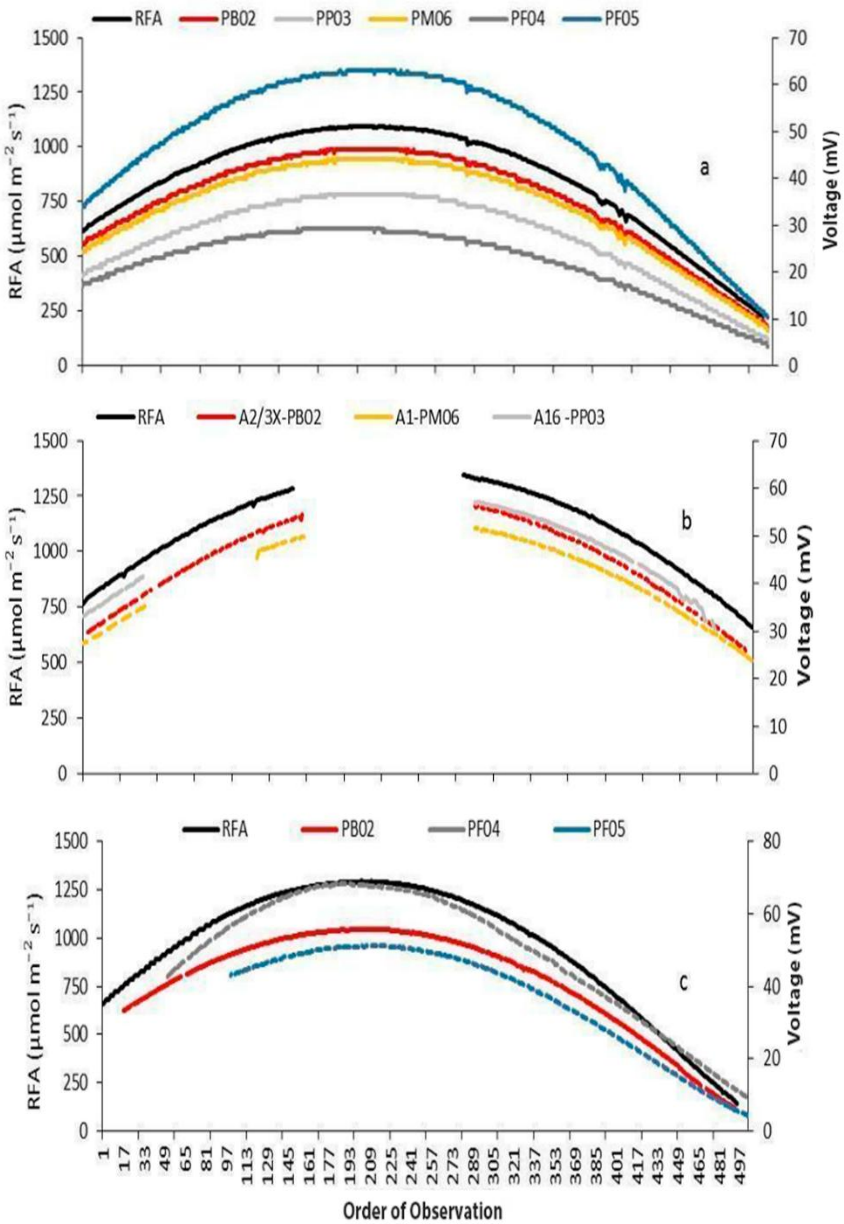
Figure 1 - Hourly evolution of global solar radiation (a) and air temperature (b) on July 21, 2023, August 29, 2023, and August 14, 2024, during the RFA measurement calibration in Santa Maria, RS



Source: research data.

The temporal evolution of RFA and the voltage measured by each FSA using the data acquisition systems of the Arduino platform, Campbell Scientific®, and Li-Cor® can be observed in Figure 2. The temporal variation of the voltage measured by each data acquisition system shows a response pattern similar to that of RFA. Alves *et al*. (2020) also found a similar temporal variation among measurement systems. This finding was essential for proceeding with further analyses.

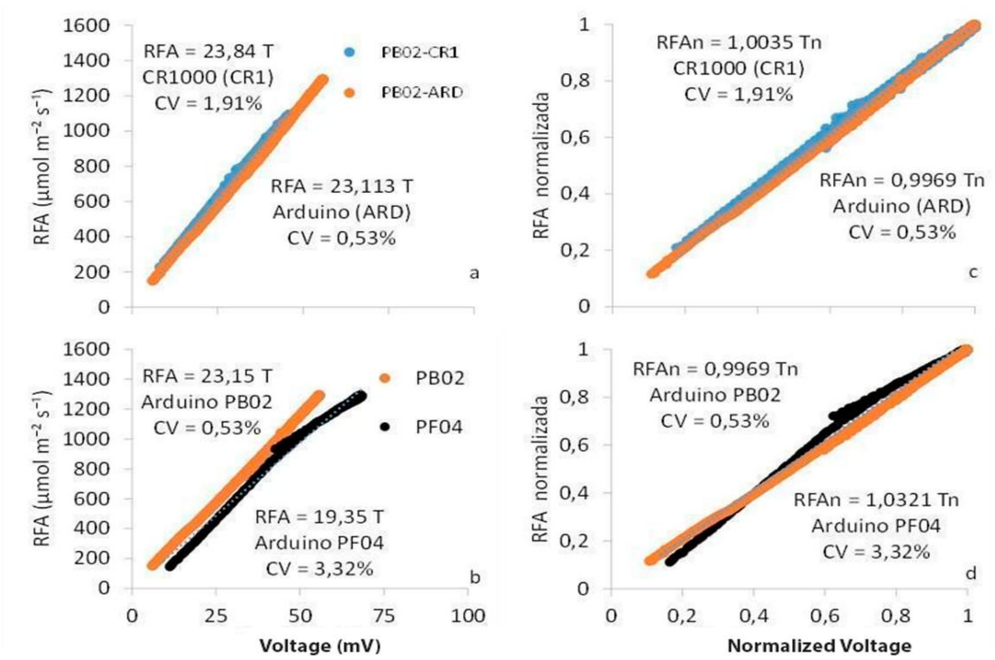
Figure 2 - Temporal evolution of the voltage measured with the FSA coupled to the CR1000 on July 21, 2023 (a), with the FSA coupled to the Arduino platform on August 29, 2023 (b), and on August 14, 2024 (c), along with the RFA measurements obtained with the Quantum sensor in Santa Maria, RS



Caption: PB02, PP03, PM06, PF04, and PF05 are prototype codes designed to accommodate each amorphous silicon photocell (FSA); A2/3X, A1, A16 represent the amplification of the FSA signal by 2/3, one, and sixteen times using the analog-to-digital converter.
Source: research data.

The calibration coefficients of the FSA connected to the Arduino platform and the CR1000 are presented in Figure 3. The coefficients of 23.84 and 23.15 μmol m^{-2} s^{-1} were very close for the calibration performed with the CR1000 and the Arduino, respectively (Figure 3a). Another important aspect was that the coefficient of variation was below 2% in both systems, demonstrating high precision (Storck *et al*., 2000). The coefficient of variation in the comparison of extreme results obtained with the Arduino on August 14, 2024, was at most 3.32%. Moreover, the angular coefficients in the data normalization process ranged from 0.9969 to 1.0321, indicating a strong linear relationship with a directly proportional variation (Figure 3d).

Figure 3 - Calibration coefficients of the FSA connected to the Arduino platform on August 14, 2024, and to the CR1000 on July 21, 2023 (a); extreme calibration results with the Arduino platform on August 14, 2024 (b) in phase 1; and respective data obtained in the normalization of RFA and voltage (c) and (d) in phase 2.



Caption: PB02 and PF04 are prototype codes designed to accommodate each amorphous silicon photocell (FSA).
Source: research data.

All the calibration coefficients and other statistical results obtained with original and normalized data for RFA measurement using different photocells connected to the CR1000 datalogger and the Arduino platform are presented in Table 1. With the normalized data, it can be stated that the different resolution gains, varying the amplification range of the voltage measurement in the ADC from 2/3X, 1X, and 16X, also did not influence the precision results, expressed by RMSE and CV. Just as Barnard, Findley, and Csavina (2014) observed that Arduino can be used for RFA measurement with the Quantum sensor, the results in Table 1 also suggest that Arduino can be employed for RFA measurement with the FSA.

Table 1 - Calibration coefficient (CC, μmol m^{-2} day^{-1} mV^{-1}), root mean square error (RMSE, μmol m^{-2} day^{-1}), coefficient of variation (CV, %), and coefficient of determination (R^2) for RFA measurement using different photocells connected to the CR1000 datalogger and the Arduino platform, with original and normalized values, in Santa Maria-RS

FSA	Amplification	CC	R^2	RQME	CV	-	CC	R^2	RQME	CV
Arduino										
Original values						-	**Normalized values**			
A-PB02	A2/3X	24.54	0.9989	35.30	3.28	-	1.0230	0.9989	0.0262	3.28
B-PM06	A1X	26.47	0.9994	27.13	2.52	-	1.0142	0.9994	0.0201	2.52
C- PP03	A16X	23.53	0.9998	16.28	1.51	-	0.9979	0.9998	0.0121	1.51
D- PB02	A16X	23.15	1.0000	5.28	0.53	-	0.9983	1.0000	0.0041	0.53
E- PF04	A16X	19.35	0.9990	32.73	3.32	-	1.0236	0.9990	0.0253	3.32
F- PF05	A16X	25.63	0.9997	19.05	1.93	-	1.0152	0.9997	0.0147	1.93
CR1000										
G- PB02	-	23.84	0.9997	16.20	1.91	-	1.0035	0.9997	0.0148	1.91
H- PM06	-	25.00	0.9996	16.77	1.98	-	0.9936	0.9996	0.0153	1.98
I-PP03	-	30.46	0.9988	30.52	3.61	-	1.0181	0.9988	0.0279	3.61
J- PF05	-	17.50	0.9996	18.61	2.20	-	1.0077	0.9996	0.0170	2.20
K- PF04	-	37.95	0.9969	48.72	5.76	-	1.0101	0.9969	0.0445	5.76

Source: research data.

The measurements of PAR using Amorphous Silicon Photocells (FSA) are widely applied in different crops, such as canola (Dalmago *et al*., 2018), grapevines (Cardoso *et al.*, 2010), sunflower (Lemainski *et al*., 2023), and corn (Bergamaschi *et al*., 2010). These studies employed data acquisition systems similar to the one used in this study (CR1000). Since PAR measurements exhibit variability similar to the CR1000 system, Santos *et al*. (2023) could have performed such measurements in their study, which evaluated the physiological quality of soybean seeds subjected to different storage periods in dry soil and varying temperatures. Given that the seeds were later sown in trays inside a greenhouse, it would have been beneficial to characterize the environment by measuring incident solar radiation inside the greenhouse compared to external conditions.

The similarity between the PAR sensors used in the Arduino and CR1000 systems was evident. Analyzing the calibration coefficients (CC) of each FSA, it was observed that values ranged from 19.35 to 26.47 μmol m^{-2} day^{-1} mV^{-1} in the Arduino system. The coefficient of variation (CV) fluctuated between 0.53% and 3.28%. Using the same photocells connected to the CR1000, the CC varied from 17.5 to 37.95 μmol m^{-2} day^{-1} mV^{-1}, and the CV ranged from 1.91% to 5.76% (Table 1).

Another study where PAR evaluation would have been beneficial was conducted by Dutra *et al*. (2023), who analyzed the growth of chambá (*Justicia pectoralis*) under different fertilization sources at shading levels of 0% and 80%. Understanding the available PAR for plants in different treatments could be a useful tool for explaining the observed results. Thus, the lack of PAR measurements is often linked to the limitation of measurement, recording, and sensor options.

With the advent of low-cost systems like the Arduino platform, it is possible to increase the number of measurements, thereby reducing temporal and spatial variability under plant canopies. Since error variability was similar between the two data acquisition systems, increasing the experimental precision in studies requiring PAR measurement beneath plant canopies with more extensive sampling is feasible.

The determination coefficients (R^2) obtained in this study (Table 1) are comparable to values reported in the literature, indicating feasibility. Alves *et al*. (2020) reported an R^2 of 0.957 for PAR measurements using the Arduino, suggesting strong correlation and precision. Similarly, Rêgo and Sanagiotto (2015) found R^2 values of 0.981 and 0.956 for air temperature, indicating high accuracy, while relative humidity R^2 values ranged from 0.927 to 0.943. These results demonstrate the reliability of using the FSA for environmental studies on radiation, temperature, and humidity.

However, for linear regression analysis where the intercept is disregarded, the most relevant variable is the coefficient of variation. In the Arduino system, it ranged from 0.53% to 3.32%, while in the CR1000, it ranged from 1.91% to 5.76%. Thus, the results obtained in this study align with previously reported values for other meteorological variables, reinforcing the feasibility and accuracy of using the Arduino-based data acquisition system for measuring photosynthetically active radiation. Besides its technical viability, further studies are recommended to assess the economic feasibility of using this platform for PAR measurements.

4 Conclusion

The errors observed in photosynthetically active radiation measurements using the Arduino platform are similar to those observed with the CR1000 datalogger. The Arduino-based data collection system allows data storage, making it a viable, low-cost, and efficient option for measuring photosynthetically active radiation.

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