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Design and Develop a Portable SPAD Meter using Arduino Nano and Optical Sensing Components

Sachinkumar Nandgude
Mahatma Phule Krishi Vidyapeeth
Himalaya Ganachari
01swce14@gmail.com

Mahatma Phule Krishi Vidyapeeth
Sangita Shinde
Mahatma Phule Krishi Vidyapeeth
Prasad Deshmukh
Mahatma Phule Krishi Vidyapeeth
Kiran Ransing
Mahatma Phule Krishi Vidyapeeth
Aishwarya Desai
Mahatma Phule Krishi Vidyapeeth

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Design and Develop a Portable SPAD Meter using Arduino Nano and Optical Sensing Components

ABSTRACT

The study titled *"Development and Performance Evaluation of a Low-Cost DIY SPAD Meter for Chlorophyll Estimation"* aims to develop an accurate, portable, and cost-effective device for estimating leaf chlorophyll content using optical sensing techniques. The system is based on the principle of differential light transmission through plant leaves using red (~650 nm) and infrared (~940 nm) wavelengths. A TSL2561 digital light sensor was employed to measure transmitted light intensity, while an Arduino Nano microcontroller was used for data acquisition, processing, and display of SPAD values on an OLED interface. A logarithmic transmittance ratio (R) was computed from the measured intensities to capture the variation in chlorophyll content during measurement. Calibration of the developed device was performed using a standard SPAD-502 chlorophyll meter, and a regression-based approach was adopted to establish the relationship between the measured and reference SPAD values. The calibration model obtained demonstrated a strong correlation, with a coefficient of determination (R^2) of 0.8822 and a correlation coefficient of 0.9392. The developed system showed high accuracy, with prediction errors within ±1 to ±8 SPAD units, indicating reliable performance comparable to the commercial instrument. The study highlights the effectiveness of integrating low-cost hardware components with microcontroller-based processing for real-time chlorophyll estimation. The developed device provides a scalable, user-friendly, and economical solution for non-destructive plant monitoring. The proposed methodology can be extended to other crops and agricultural applications, supporting precision farming and efficient nutrient management practices.

Keywords: Chlorophyll; SPAD; Arduino Nano; TSL2561; Optical sensing; Precision agriculture

1. INTRODUCTION

Chlorophyll is an essential pigment responsible for photosynthesis in plants and plays a crucial role in determining plant health, growth, and productivity (*Taiz & Zeiger, 2015; Lichtenthaler, 1987*). Which is closely related to nitrogen status, photosynthetic capacity, and overall crop yield. Therefore, accurate and timely estimation of chlorophyll content has significant importance in precision agriculture, crop management, and nutrient optimization (*Richardson et al., 2002; Uddling et al., 2007*).

Traditional methods for chlorophyll estimation involves destructive laboratory analysis using chemical extraction (*Arnon, 1949; Porra et al., 1989*). Although these methods provide accurate results, they are time-consuming, labour-intensive, and unsuitable for real-time field applications (*Markwell et al., 1995; Netto et al., 2005*). To overcome these limitations, non-destructive optical techniques have been widely adopted. Among these, the SPAD-502 chlorophyll meter becomes a standard instrument due to its rapid measurement capability and ease of use (*Minolta, 1989; Markwell et al., 1995*).

The working principle of SPAD meters is based on the differential absorption of light, primarily in the red (~650 nm) and infrared (~940 nm) regions (*Minolta, 1989; Monje & Bugbee, 1992*). This principle is derived from the Beer-Lambert Law, based on the ratio of light absorbance to the concentration of absorbing substances. Chlorophyll strongly absorbs red light while allowing infrared light to pass through, enabling estimation of chlorophyll content through transmittance measurements of red & infrared light (*Lichtenthaler, 1987; Markwell et al., 1995*). John Markwell et al. 1995 established calibration relationships between SPAD readings and actual chlorophyll concentration, forming the foundation for modern SPAD-based chlorophyll measurements.

Despite their advantages, commercial SPAD meters are expensive and often inaccessible to students, researchers, and small-scale farmers, particularly in developing countries (*Sookchalearn & Abdullakasim, 2017; Křížová et al., 2022*). In recent years, several researchers have focused on developing low-cost alternatives using microcontrollers, light sensors, and LED-based optical systems. These studies have demonstrated that low-cost devices can achieve high accuracy (R^2 values typically ranging from 0.87 to 0.97) when properly calibrated against standard instruments (Kamarianakis & Panagiotakis, 2023; *Khaled et al., 2021; Andrianto et al., 2020; Nasution et al., 2022*).

The integration of microcontroller platforms such as Arduino Nano with digital light sensors has enabled the development of compact, portable, and energy-efficient chlorophyll meters. These systems utilize red and infrared LEDs as light sources and measure transmission of light through leaves using photodetectors or digital sensors. By applying appropriate mathematical models and calibration techniques, the measured signals can be converted into SPAD-equivalent values (*Du et al., 2022*; *Bordoloi, 2023).*

In this context, the present study aims to design and develop a low-cost microcontroller-based SPAD meter using a TSL2561 light sensor and Arduino Nano. The system employs a logarithmic

transmittance ratio model to estimate chlorophyll content and incorporates a calibration equation derived from regression analysis with a standard SPAD-502 meter. The developed device is intended to provide a cost-effective, portable, and reliable solution for non-destructive chlorophyll estimation, suitable for field applications and academic use.

2. MATERIALS AND METHOD

Components such as hardware and software involved in design and development of DIY SPAD meter were discussed in this section as follows.

2.1 Hardware Components

2.1.1 Arduino Nano

Arduino Nano as illustrate in fig. 1, is a small microcontroller board based on ATmega328P. It works at 5V with a clock speed of 16 MHz and has multiple digital and analog pins for connecting components. It supports communication methods like I2C, SPI, and UART, making it easy to connect sensors and displays.

2.1.2 TSL2561 Light Sensor

The TSL2561 is a digital light sensor that can measure both visible and infrared light as shown in fig. 2. It works over a wide range of light intensity and connects to the microcontroller using I2C communication. It has two sensors—one for visible light and one for infrared—which helps in accurate measurement.

2.1.3 Red LED (~650 nm)

The red LED emits light at around 650 nm, which is strongly absorbed by chlorophyll in leaves. It works at low voltage (about 1.8–2.2V) and current (10–20 mA). As it is illustrate in fig. 3.

2.1.4 Infrared LED (~940 nm)

The infrared LED as shown in fig. 4 emits light in the near-infrared region (~940 nm), which is minimally absorbed by chlorophyll. It operates at a forward voltage of approximately 1.2–1.5V and similar current ratings as the red LED.

2.1.5 OLED Display (0.96 inch)

The OLED display is a 128×64-pixel screen that operates using I2C communication. It functions at 3.3V–5V and consumes low power. The display provides high contrast and wide viewing angles, suitable for portable devices as shown in fig. 5.

2.1.6 Push Buttons / Tactile Switches

Push buttons (tactile switches) are electromechanical input devices used for user interaction, which are shown in fig. 6. They operate as momentary switches at low voltage (5V). In this system, they are used for calibration and measurement operations. When pressed, they send signals to the microcontroller to

trigger functions. Pull-up resistors ensure stable signal detection. Their compact size makes them suitable for embedded applications.

2.1.7 On/Off Switch (Rocker Switch)

The on/off switch is used to control the power supply (fig. 7). A rocker switch is commonly used due to its durability. It allows safe switching without disconnecting the battery. The switch is rated for low voltage DC operation.

2.1.8 Resistors

Resistors (Fig. 8) are passive components used to limit current and divide voltage. They are available in different resistance values measured in ohms (Ω).

2.1.9 Power Supply (7.4V Lithium Battery)

A 7.4V lithium battery (two Li-ion cells in series) is used to power the system. It provides a stable and rechargeable power source. The battery typically has a capacity of 2000–3000 Mah, allowing extended use (fig. 9). It ensures continuous operation of the microcontroller, sensor, and display. It supports portable field applications.

2.1.10 Charging Module (TP4056)

The charging module (TP4056) protects lithium-ion batteries against overcharging, over-discharging, and short circuits (fig. 10). Operates at 5V input and regulates charging automatically. Indicates charging status by LEDs indicator for. It ensures safe and efficient charging.

2.1.11 Jumper Wires

Jumper wires are flexible wires available in different configuration (fig. 11). Used for prototyping and making connections between components. They allow easy modification and debugging and ensures safe operation.

2.1.12 Breadboard

A breadboard is a reusable platform used for designing and testing electronic circuits without soldering as shows in fig. 12. It consists of interconnected rows and columns that allow easy component placement. Power rails are used to distribute voltage and ground. It helps in quick modification and troubleshooting of circuits.

2.1.13 2-Cell Battery Holder

A 2-cell battery holder is used to hold two batteries and supply power to the circuit. It provides a stable voltage output through its terminals. This component ensures portability and independent operation. 2-Cell battery holder is as shown in fig. 13.

2.1.14 USB Connecting Cable

A USB connecting cable used for connecting the Arduino Nano to a computer or power source as shown in fig.14. It enables data transfer and serial communication for programming. The cable also supplies power during testing and development. It is essential for uploading code to Arduino Nano and monitoring outputs.

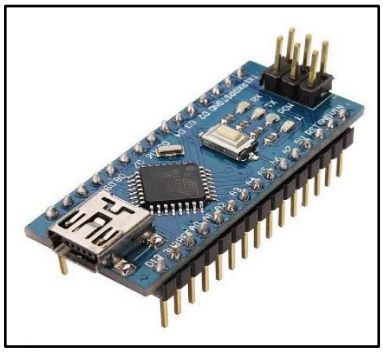


Fig. 1 Arduino Nano

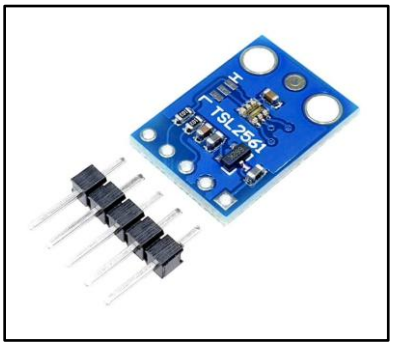


Fig. 2 TSL2561 Light Sensor

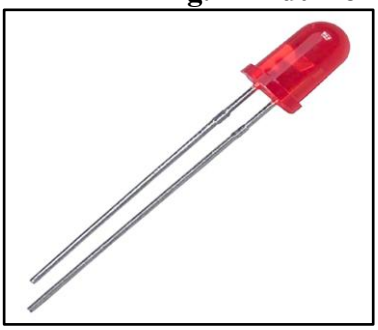


Fig. 3 Red LED (~650 nm)

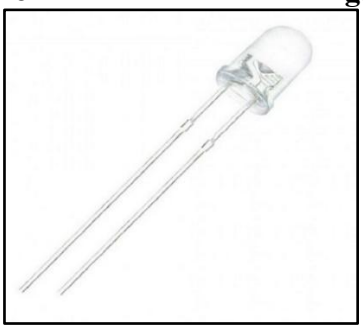


Fig. 4 Infrared LED (~940 nm)

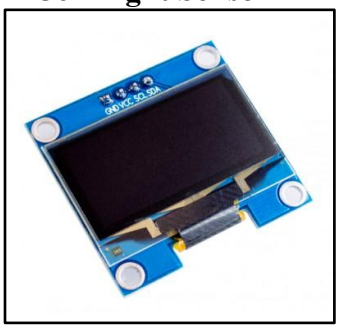


Fig. 5 OLED Display (0.96 inch)



Fig. 6 Push Buttons / Tactile Switches

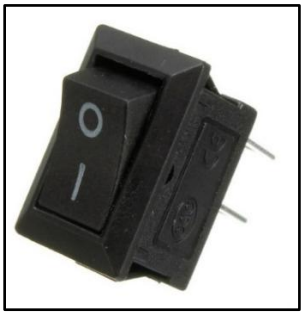


Fig. 7 On/Off Switch (Rocker Switch)

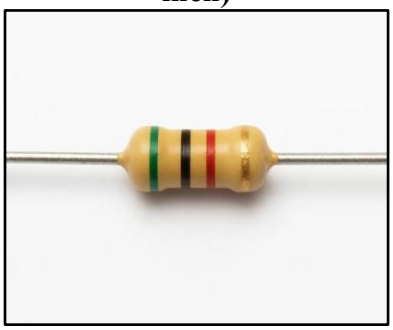


Fig. 8 Resistors



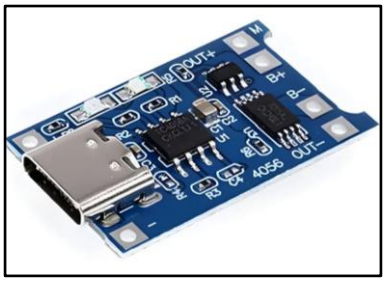




Fig. 9 Power Supply (7.4V Lithium Battery)

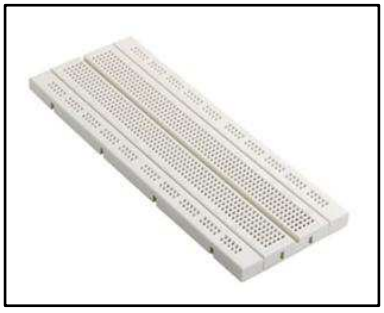


Fig. 12 Breadboard

Fig.10 Charging Module (TP4056)



Fig. 13 2-Cell Battery Holder

Fig. 11 Jumper Wires



Fig. 14 USB Connecting Cable

2.2 Software Used

2.2.1 Arduino IDE

Arduino Integrated Development Environment (IDE) is a software platform used to write, compile, and upload programs to the Arduino Nano microcontroller. It uses simple C/C^{++} programming language, making it easy for beginners and developers to create embedded system applications. The IDE provides a user-friendly interface for coding, error checking, and program uploading through a USB connection. Software interface is as shown in fig. 15.

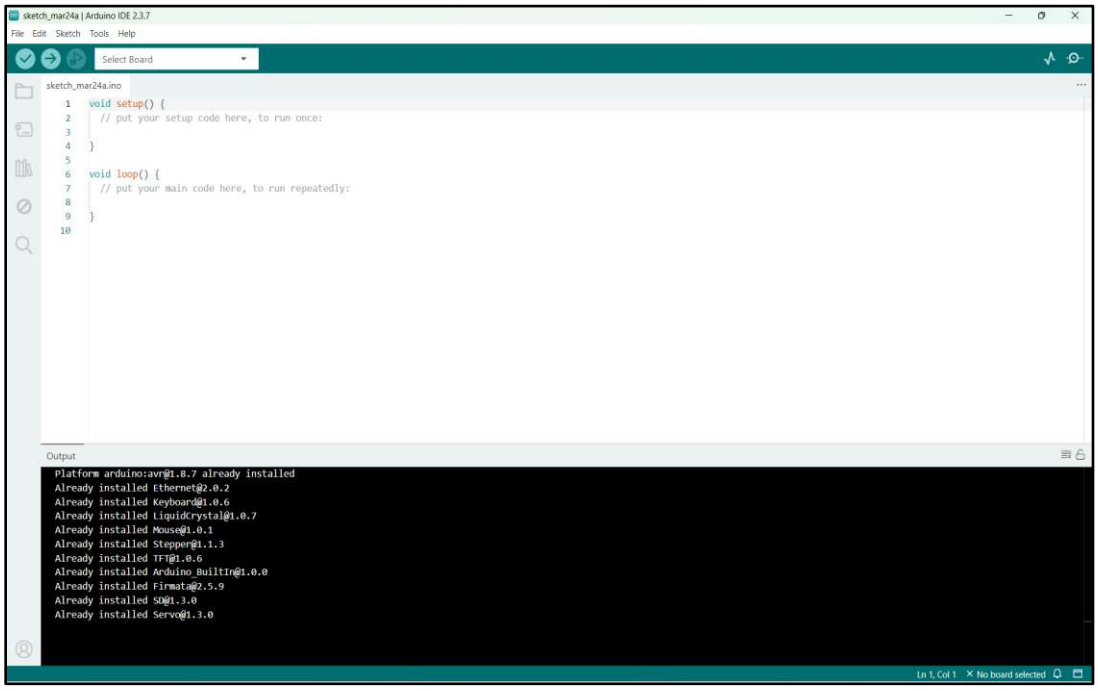


Fig. 15 Arduino IDE Interface Used for Programming the Arduino Nano in the DIY SPAD Meter

The following libraries are used in the program to simplify coding and improve functionality:

1) **Wire.h** – Used for I2C communication between Arduino, sensor, and display

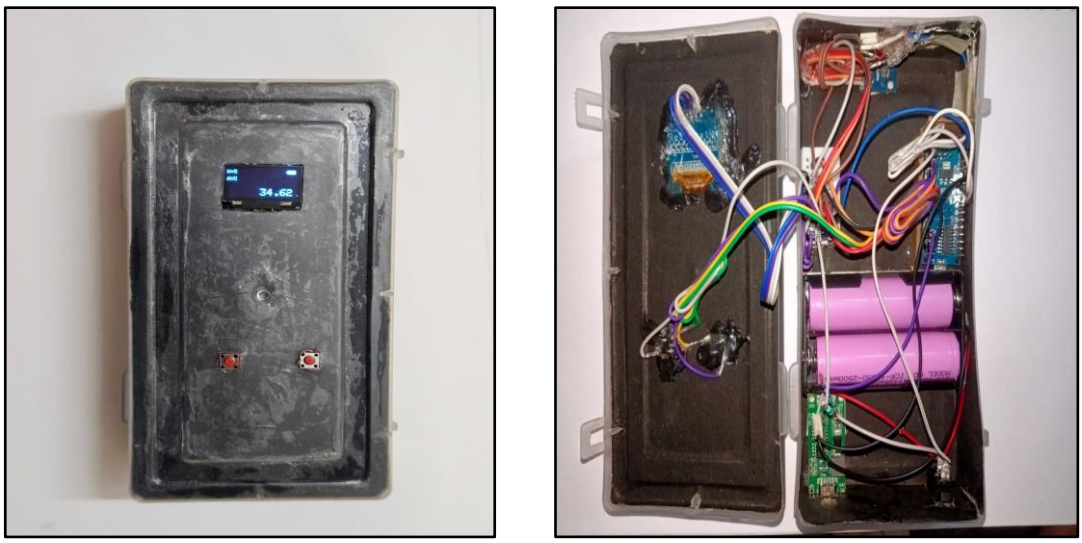
2) **Adafruit_Sensor.h** – Provides a common interface for sensor data handling
3) **Adafruit_TSL2561_U.h** – Used to operate the TSL2561 light sensor
4) **Adafruit_GFX.h** – Used for drawing text and graphics on the display
5) **Adafruit_SSD1306.h** – Used to control the OLED display

The Arduino IDE plays an important role in implementing the system logic, performing calculations, and ensuring smooth operation of the SPAD meter.

2.3 Circuit Diagram

Components consist of software which involves Arduino IDE platform, while, hardware involves Arduino Nano, Red LED (~650 nm), Infrared LED (~940 nm), TSL2561 digital light sensor, OLED 128×64 display module, push buttons, and a 7.4V lithium battery power supply. Fig. 16 (a) shows the external view of compact handheld device with an OLED display, push buttons and a leaf holder for positioning the sample. Besides, fig. 16 (b) illustrates internal view of DIY SPAD meter where connection of components such as the Arduino Nano, red and infrared LEDs, TSL2561 Light Sensor, battery, charging module, and associated circuitry are connected as shown in fig. 17. Required specification of the parameters used in the developed DIY SPAD meter is given in the table 1.

The Both LEDs and TSL2561 Light Sensor was aligned opposite to each other, ensuring that light emitted by LEDs transmitted through the leaf and sensed by sensor standing across flow. An Arduino Nano, act as the main control and processing unit of SAPD meter. A red LED and infrared LED used as optical sources connected Arduino through 200 Ω and 220 Ω resistor, respectively, and activates sequentially during the measurement. Chlorophyll strongly absorbs radiation in red, whereas, the near-infrared is considerably lower, therefore, comparison of the two transmitted signals provide information related to chlorophyll concentration. The light transmitted through the leaf is detected by the TSL2561 light sensor, which communicates with Arduino through I^2C interface. In the circuit, the SDA and SCL terminals of te TSL2561 are connected to the Arduino Nano's A4 and A5 pins, respectively, while the sensor is supplied with 3.3 V and connected to the common ground. The 128×64 OLED display is connected to the same I^2C bus, wit its SDA and SCL lines connected to A4 and A5, respectively, allowing the Arduino to display the measured optical values, calculated transmission ratio and final chlorophyll or SPAD value. The two push buttons connect to Arduino at D8 and D7, provides user control; one button programmed to initiate the measurement sequence, whereas second used for calibration. The power supply consist of two 18650 lithium ion cells providing a nominal 7.4 V with the battery connected through an ON/OFF switch, battery charging controller at one end and another end connected the Arduino at A0 with 10.0 kΩ resistor. Other end of ON/OFF switch connects Arduino at VIN. Finally, common ground is maintained between the Arduino, Optical Sensor, Display LED and Control circuitry to provide a common electrical reference.



(a) (b)

Fig. 16 The DIY SPAD meter: external (a) and internal view (b)

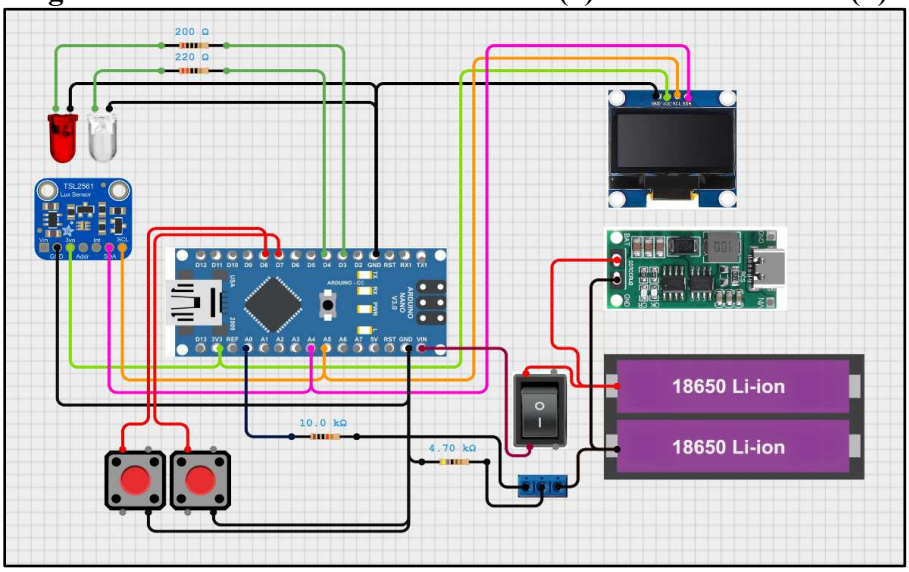


Fig. 17 Circuit Diagram

Table 1. System Specifications of Developed DIY SPAD Meter

Parameter	Specification
Microcontroller	Arduino Nano (ATmega328P)
Operating Voltage	5 V
Clock Speed	16 MHz
Light Sensor	TSL2561 Digital Light Sensor
Light Sources	Red LED (~650 nm), IR LED (~940 nm)
Display Module	0.96" OLED (128 × 64, I2C)
User Input	Push Buttons (Calibration & Measurement)

Parameter	Specification
Communication Protocol	I2C (Sensor & Display)
Power Supply	7.4 V Li-ion Battery (2-cell)
Charging Module	TP4056
Measurement Principle	Optical Transmission Method
Calibration Model	Linear Regression Model
Calibration Equation	SPAD = 0.897 × SPAD_DIY + 5.1487
Measurement Range	Approx. 20 – 70 SPAD Units
Accuracy	91.86 %
Number of Samples Tested	150
Portability	Handheld, Field Operable

2.4 Measurement Procedure

The working principle of the developed DIY SPAD meter is based on the differential absorption and transmission characteristics of light through plant leaf tissue. Chlorophyll pigments present in leaves strongly absorb light in the red region of the visible spectrum (~650 nm), while allowing near-infrared (IR) light (~940 nm) to pass through with minimal absorption. This difference in light interaction forms the basis for estimating chlorophyll content in a non-destructive manner. Initially powering ON the device through the rocker switch. Where, the system undergoes an initialization phase of configuration and verification of the Arduino Nano, TSL2561 Light Sensor, and OLED display. Once initialization is complete, the system enters standby mode and indicates readiness for operation by displaying on display "SPAD METER READY".

Prior to measurement, system need to undergo a calibration procedure, which was performed by pressing the calibration button in the absence of a leaf (void – without placing a leaf between the LEDs and the sensor). This step records the reference transmittance values of both red and infrared wavelengths. These readings, denoted as IR_{ref} and RED_{ref} represent the maximum transmitted light intensity. Sequentially similar procedure perform with leaf, when a leaf was placed between the LEDs and Sensor, part of the red light is absorbed by chlorophyll, while infrared light mostly transmitted through leaf. The sensor records the transmitted light intensities as *IR* and *RED*. The ratio of transmitted light intensities was calculated using a logarithmic relationship to minimize the effect of variations in leaf thickness, structure, and external conditions. The ratio (R) expressed as:

$$R = \log_{10}\left(\frac{IR/IR_{ref}}{RED/RED_{ref}}\right)$$

SPAD value for the same leaf samples measured using a standard SPAD meter and recorded as, $SPAD_{real}$ Scaling Constant (k) computed as given below,

$$k_i = \frac{SPAD_{real}}{R}$$

$$k_{avg} = \frac{\sum k_i}{n}$$

Where,

n= number of samples

The calculated ratio was then converted into a SPAD value using a scaling factor as given below,

$$SPAD_{DIY} = k_{avg} \times R$$

Moreover, a calibration equation was derived from linear regression analysis and Non-Linear (Exponential) Calibration from equation given below,

Linear regression analysis:

$$SPAD_{real} = m \cdot SPAD_{DIY} + c$$

Non-Linear (Exponential) Calibration:

$$\log_{10}(SPAD_{real}) = a \cdot SPAD_{DIY} + b$$

Where:

a= slope

b= intercept

Based on high values of R^2 of above models, calibration model was selected for the implementation in the microcontroller for real-time SPAD estimation.

Some other mechanism for basic error detection were incorporated, such as identification of low signal levels or improper sample placement, for reliable measurements and minimisation of error. The detailed operational flow chart shown in fig.18.

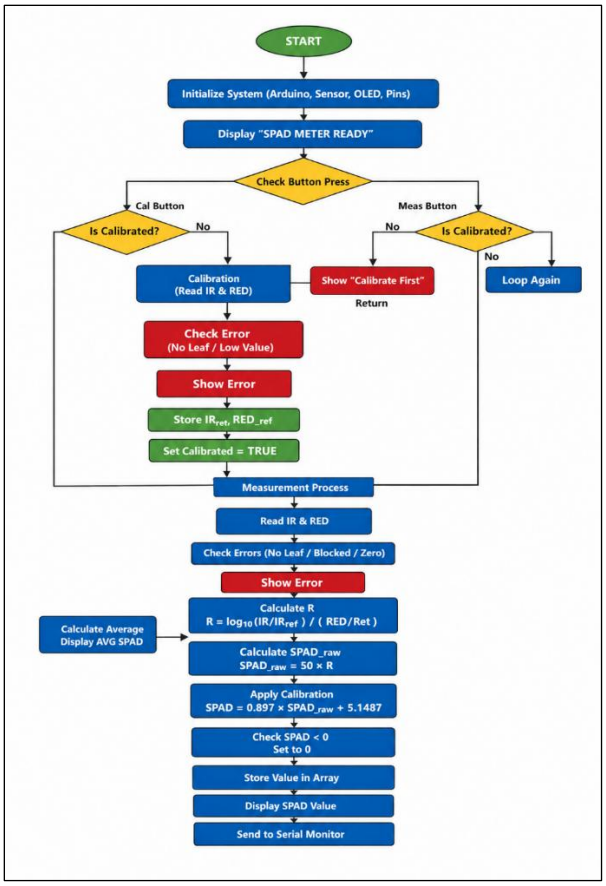


Fig. 18 Operational Flowchart of the Chlorophyll Measurement

2.5 Calibration Procedure

Calibration was performed using a linear regression analysis and Non-Linear (Exponential) Calibration model with reference to standard commercial SPAD meter as elaborated in section measurement procedure.

2.6 Validation of the DIY SPAD Meter

Validation of the DIY SPAD meter was initially performed by determining the R^2 between the both calibration model and Standard SPAD meter. Further, determined the accuracy of meter using following equation as given below.

$$Accuracy(\%) = \left(1 - \frac{|\ SPAD_{standard} - SPAD_{DIY}\ |}{SPAD_{standard}}\right) \times 100$$

Where,

$SPAD_{standard}$ – Values derived from Standard SPAD meter.

$SPAD_{DIY}$ – Values derived from Developed SPAD meter.

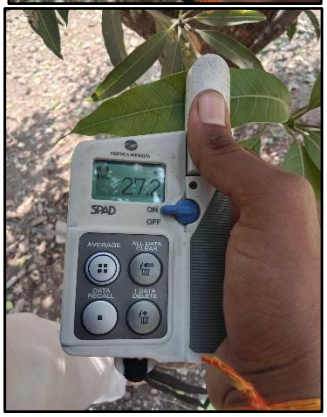
3. RESULT AND DISCUSSION

A total of **150 leaf samples** were collected from different crops to ensure variability in chlorophyll content. Out of which 70% i.e. 105 were used for testing and 30 % i.e. 45 for validation. The samples were selected to represent a wide range of SPAD values, from low to high chlorophyll concentration. Some pictures of field observation were shown in table 2.

Table 2. Field observations during the development of SPAD meters.

Crop Name	Standard SPAD meter	DIY SPAD meter
Tomato		
Sponge Gourd		
Chilli		

Crop Name	Standard SPAD meter	DIY SPAD meter
Lemon		
Sweet Lemon		
Sapota		
Jambhul		

Crop Name	Standard SPAD meter	DIY SPAD meter
Maize		
Bamboo		
Mango		

3.1 Scaling Constant (k)

Initially, for determination of scaling constant (k) IR, RED, IR_{ref}, RED_{ref} and Real values obtained from standard SPAD are needed as discussed in section **measurement procedure.** Corresponding values of 105 samples as shown in table 3.

Table 3. Scaling constant of 105 samples

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
1	Mango	Mangifera indica	85	881	22	37	42.1	53.31	37.4
2	Ashoka	Saraca asoca	85	881	23	83	26	56.74	21.3

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
3	Moong	Vigna radiata	85	881	27	41	33.9	40.64	40.1
4	Neem	Azadirachta indica	85	881	28	86	27.7	52.44	24.8
5	Peepal	Ficus religiosa	85	881	33	66	33.3	46.6	34.1
6	Rui	Calotropis gigantea	85	881	23	7	70.5	46.01	75
7	Ber	Ziziphus mauritiana	85	881	22	44	34.6	48.42	34.1
8	Banyan	Ficus benghalensis	85	881	22	22	55.9	55.04	50.2
9	Golden dewdrop	Duranta erecta	85	881	30	168	12.8	47.87	11.8
10	Ashanti blood	Alternanthera ficoidea	85	881	27	36	41.7	46.82	42.9
11	Sadabahar	Catharanthus roseus	85	881	25	19	52.1	45.91	57.1
12	Custard apple	Annona squamosa	85	881	25	67	28.5	48.52	27.8
13	Chafa	Plumeria rubra	85	881	18	39	37.1	54.58	32.4
14	Jasmine	Jasminum sambac	85	881	29	73	29.6	48.16	29.1
15	Kamini	Murraya paniculata	85	881	25	22	50.8	47.43	51.9
16	Coatbuttons	Tridax procumbens	85	881	20	22	43	44.14	47.1
17	Bamboo	Bambusa vulgaris	85	881	25	33	41.4	46.26	43.1
18	Needle palm	Rhapidophyllum hystrix	85	881	19	8	65.4	47.01	68
19	Christ plant	Euphorbia milii	85	881	15	12	57.9	52.05	54
20	Five fingers	Schefflera arboricola	85	881	25	111	20.1	54.59	16.8
21	New Zealand flax	Phormium tenax	85	881	25	168	10.9	57.92	7.8
22	Sago palm	Cycas revoluta	85	881	18	7	70.6	49.52	69.7
23	Croton	Codiaeum variegatum	85	881	22	26	43.7	46.34	45.8
24	Weeping fig	Ficus benjamina	85	881	20	43	38.1	55.77	32.6
25	Rose	Rosa indica	85	881	20	43	39.5	57.82	32.6

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
26	Majesty palm	*Ravenea rivularis*	85	881	28	119	23	59.41	17.8
27	Lady palm	*Rhapis excelsa*	85	881	28	102	25	55.05	21.1
28	Black turmeric	*Curcuma caesia*	85	881	28	103	22.7	50.46	20.9
29	Agave	*Agave americana*	85	881	18	11	59.6	48.48	59.9
30	Ti plant	*Cordyline fruticosa*	85	881	23	16	56.6	48.25	57.1
31	Temen	*Tecoma stans*	85	881	21	32	37.6	45.16	40
32	Peace Lily	*Spathiphyllum wallisii*	85	881	28	35	48.7	53.01	44.3
33	Dumb Cane	*Dieffenbachia seguine*	85	881	27	55	35.1	49.68	33.7
34	Dracaena limelight	*Dracaena fragrans*	85	881	26	14	57.7	44.92	62.6
35	Burgundy glass	*Tradescantia spathacea*	85	881	26	23	48.7	45.57	51.8
36	Bal fourvaralia	*Bougainvillea spectabilis*	85	881	26	37	38.1	44.18	41.5
37	Sambor cheesa	*Sansevieria trifasciata*	85	881	27	72	30.2	51.22	27.9
38	African milk	*Euphorbia trigona*	85	881	17	22	42.5	47.03	43.6
39	Jungle geranium	*Ixora coccinea*	85	881	26	38	40.1	47.14	40.9
40	Ixora	*Ixora coccinea*	85	881	22	24	45.4	46.43	47.3
41	Buddha belly	*Jatropha podagrica*	85	881	24	18	54.7	47.96	55.4
42	Football lily	*Scadoxus multiflorus*	85	881	24	63	23.2	38.9	28.2
43	Hibiscus	*Hibiscus rosa-sinensis*	85	881	28	70	31.3	50.68	29.3
44	Heliconia	*Heliconia rostrata*	85	881	33	18	58.1	45.43	62.3
45	Copper leaf	*Acalypha wilkesiana*	85	881	24	43	37.8	49.59	36.5
46	Jamaican cherry	*Muntingia calabura*	85	881	23	38	43.2	54.17	38.7

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
47	Almond	*Terminalia catappa*	85	881	24	75	28.8	55.31	24.4
48	Karonda	*Carissa carandas*	85	881	27	65	33.7	53.15	30.1
49	Bracts	*Bougainvillea glabra*	85	881	13	13	51.7	50.91	49.2
50	Palush	*Butea monosperma*	85	881	30	46	34.8	41.93	39.9
51	Oyster	*Tradescantia spathacea*	85	881	21	30	35.5	41.25	41.4
52	Golden trumpet	*Allamanda cathartica*	85	881	15	16	53.2	53.87	47.8
53	Cardboard palm	*Zamia furfuracea*	85	881	14	19	41.6	47.12	42.5
54	White bougainvillea	*Bougainvillea spectabilis*	85	881	26	17	50.6	42.16	58.4
55	Coconut	*Cocos nucifera*	85	881	20	81	20	49.01	18.8
56	Golden shower	*Cassia fistula*	85	881	27	61	29.4	44.44	31.5
57	Mexican sunflower	*Tithonia diversifolia*	85	881	25	37	41.2	48.74	40.7
58	Blue plumbago	*Plumbago auriculata*	85	881	33	65	29.2	40.49	34.5
59	Trishul croton	*Codiaeum variegatum*	85	881	13	37	26.5	47.21	26.5
60	Nilgiri	*Eucalyptus globulus*	85	881	30	47	37.7	45.94	39.4
61	Tulsi	*Ocimum tenuiflorum*	85	881	25	25	41.6	40.96	41.9
62	One leaf Senna	*Senna occidentalis*	85	881	23	14	58.3	47.35	60
63	Bethea	*Bougainvillea spectabilis*	85	881	25	58	37.5	57.69	30.9
64	Common purslane	*Portulaca oleracea*	85	881	34	103	28.5	53.35	25.1
65	Spinach	*Spinacia oleracea*	85	881	32	38	52.5	55.8	45.4
66	Pig weed	*Amaranthus viridis*	85	881	20	95	33.1	97.68	24.1

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
67	Bottle gourd	*Lagenaria siceraria*	85	881	31	52	41.4	52.34	37.9
68	Wall Dudhi	*Euphorbia hirta*	85	881	23	9	73.5	51.65	69.5
69	Wild melon	*Cucumis melo var. agrestis*	85	881	31	21	56.2	47.44	57.6
70	Tomato	*Solanum lycopersicum*	85	881	33	54	36.7	45.78	38.5
71	Sunn hemp	*Crotalaria juncea*	85	881	37	118	21.1	41.22	24
72	Silver nightshade	*Solanum elaeagnifolium*	85	881	57	105	35.1	46.78	35.7
73	Lady finger	*Abelmoschus esculentus*	85	881	28	24	52.3	48.31	52.5
74	Chilli	*Capsicum annuum*	85	881	27	11	75.2	53.5	68.7
75	Brinjal	*Solanum melongena*	85	881	26	55	42.2	61.14	32.9
76	Glacora	*Gliricidia sepium*	85	881	22	31	60.5	69.81	41.7
77	Drumstick	*Moringa oleifera*	85	881	35	70	58.4	81.73	34.1
78	Watermelon	*Citrullus lanatus*	85	881	26	58	37.3	55.91	31.8
79	Cauliflower	*Brassica oleracea var. botrytis*	85	881	26	46	39	50.8	36.8
80	Anonmoua	*Annona muricata*	85	881	28	28	47.2	46.48	49.2
81	Red root pigweed	*Amaranthus retroflexus*	85	881	28	18	51.3	42.49	58.8
82	Bitter gourd	*Momordica charantia*	85	881	32	36	40.9	42.41	40.6
83	Luffa	*Luffa acutangula*	85	881	30	75	25.6	41.45	29.3
84	Gulvel	*Tinospora cordifolia*	85	881	24	48	38.9	54.44	34.1
85	Stinking Passion flower	*Passiflora foetida*	85	881	25	45	36.9	48.53	36.4
86	Fullibutton weed	*Spermacoce alata*	85	881	35	15	40.4	29.2	35.7

Sr. No.	Common Name	Botanical/Scientific Name	IR_{ref}	RED_{ref}	IR	RED	Standard SPAD	k_i	DIY SPAD
87	Partheniu m	*Parthenium hysterophorus*	85	881	25	20	52.7	47.37	48.3
88	Garlic	*Allium sativum*	85	881	18	20	45	46.4	40.9
89	Pink Mexican Petunia	*Ruellia simplex*	85	881	25	28	44.3	45.84	46.7
90	Lantana camara	*Lantana camara*	85	881	25	40	38.3	47.2	35.9
91	Pumpkin	*Cucurbita maxima*	85	881	55	76	37.6	42.97	42.2
92	Simple leaf Chesttree	*Vitex trifolia*	85	881	40	120	29.7	55.16	25.3
93	Sesame	*Sesamum indicum*	85	881	41	122	27.5	50.74	25.5
94	Licorice	*Glycyrrhiza glabra*	85	881	30	58	38.7	53.07	35.6
95	Egg plant	*Solanum melongena*	85	881	26	63	35.7	56.56	30
96	Rubber vine	*Cryptostegia grandiflora*	85	881	26	85	22.7	45.3	23.5
97	Lemon	*Citrus limon*	85	881	20	24	50.4	53.82	54
98	Arjuna Tree	*Terminalia arjuna*	85	881	28	63	36.8	55.47	31.5
99	Sweet orange	*Citrus sinensis*	85	881	19	21	43	44.23	47
100	Sapota	*Manilkara zapota*	85	881	33	163	15	46.6	14.5
101	Aster	*Callistephus chinensis*	85	881	17	45	30.5	51.45	28.5
102	Banana	*Musa paradisiaca*	85	881	30	61	30	42.41	33.8
103	Orange wild datura	*Datura metel*	85	881	35	124	26.4	56.63	21.7
104	Yellow bells	*Tecoma stans*	85	881	27	93	29.3	61.24	22.3
105	Helicindr on	*Helicteres isora*	85	881	32	150	14	40.62	14.2
					Average K			**49.92 ≈ 50**	

From table 2, variation among IR, RED and SPAD measurement can be observed. The IR values ranged from 13 to 57 with a mean of 26.50. While, RED exhibit broader range of 7 to 168 with mean of 53.37. Real SPAD and DIY SPAD values ranged from 10.9 to 75.2 and 7.8 to 75.0, with their mean of

40.22 and 39.10, respectively. Comparing two SPAD values, their average values differed by only 1.12 SPAD unit i.e. 40.22 for real SPAD and 39.10 for DIY SPAD. Also, both methods record almost identical maximum values (75.2 and 75.0, respectively), although the minimum value of DIY SPAD (7.8) was lower than that Real SPAD (10.9). The scaling constant (k) ranged from 29.2 to 97.68, with an average of 49.92. Data demonstrate variation in IR, RED, SPAD and k, while the close deviation in average and maximum value of Real SPAD and DIY SPAD suggest good agreement between the DIY SPAD and Standard SPAD measurements.

3.2 Calibration and Validation

The performance of the device was evaluated using statistical analysis and comparison with a standard SPAD meter. Both linear and non-linear calibration models were analysed, and the accuracy of the developed device was assessed across multiple vegetation. The standard readings were obtained using a SPAD-502 chlorophyll meter, which was widely used as a reference instrument. Out of 150 data samples collected, 30% of data i.e. 45 samples used for validation of results obtained from developed DIY SPAD meter.

3.3 Linear Regression Model

3.3.1 Calibration of Linear Regression Model

The relationship between the DIY SPAD values and the standard SPAD values was established using linear regression analysis with a Slope (m) and Intercept (c) were found to be 0.8970 and 5.1487, respectively. Final linear calibration equation as below,

$$SPAD_{linear} = 0.897 \times SPAD_{DIY} + 5.1487$$

Where, $SPAD_{linear}$ – Predicted Linear SPAD value and $SPAD_{DIY}$ already elaborated earlier.

3.3.2 Validation of Linear Regression Model

The value of R obtained from validation data (0.9392) indicates a strong positive correlation between the DIY SPAD readings and the standard SPAD values. While R^2 value of 0.8822 suggest, approximately 88.22% of the variation with the standard SPAD readings. The developed regression analysis as shown in fig. 19.

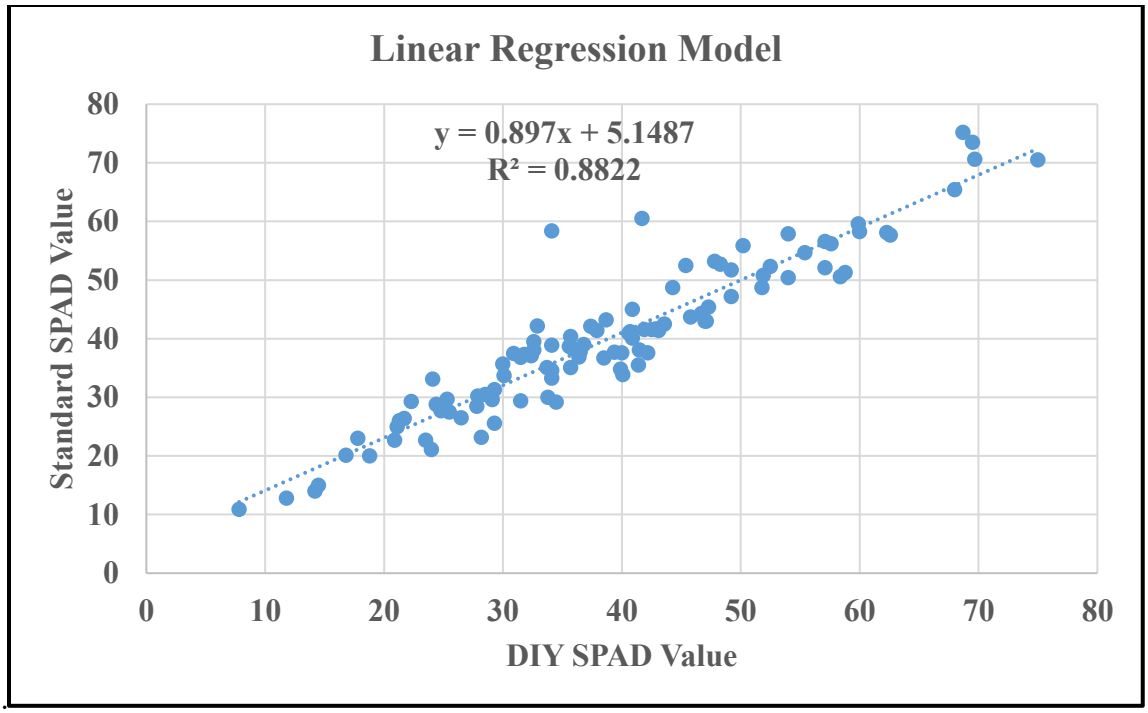


Fig. 19 Validation of Linear Calibration graph

3.4 Non-Linear (Exponential) Model

3.4.1 Calibration of Non-Linear (Exponential) Model

An exponential relationship between the DIY SPAD values and standard SPAD values were also evaluated with a slope (a) and intercept (b) of 0.0104 and 1.1712 respectively. The established equation would be as below,

$$SPAD_{exponential} = 10^{(0.0104 \cdot SPAD_{DIY} + 1.1712)}$$

Where, $SPAD_{exponential}$ – Predicted exponential SPAD Values and $SPAD_{DIY}$ already elaborated earlier.

3.4.2 Validation of Non-Linear (Exponential) Regression Model

Correlation coefficient for this model found to be 0.9127, which also, emphasising strong co-relation between the DIY SPAD and Standard SPAD measurement. Similarly, R^2 values found to be 0.8330, indicating establishment of non-linear relationship between them, as shown in fig. 20.

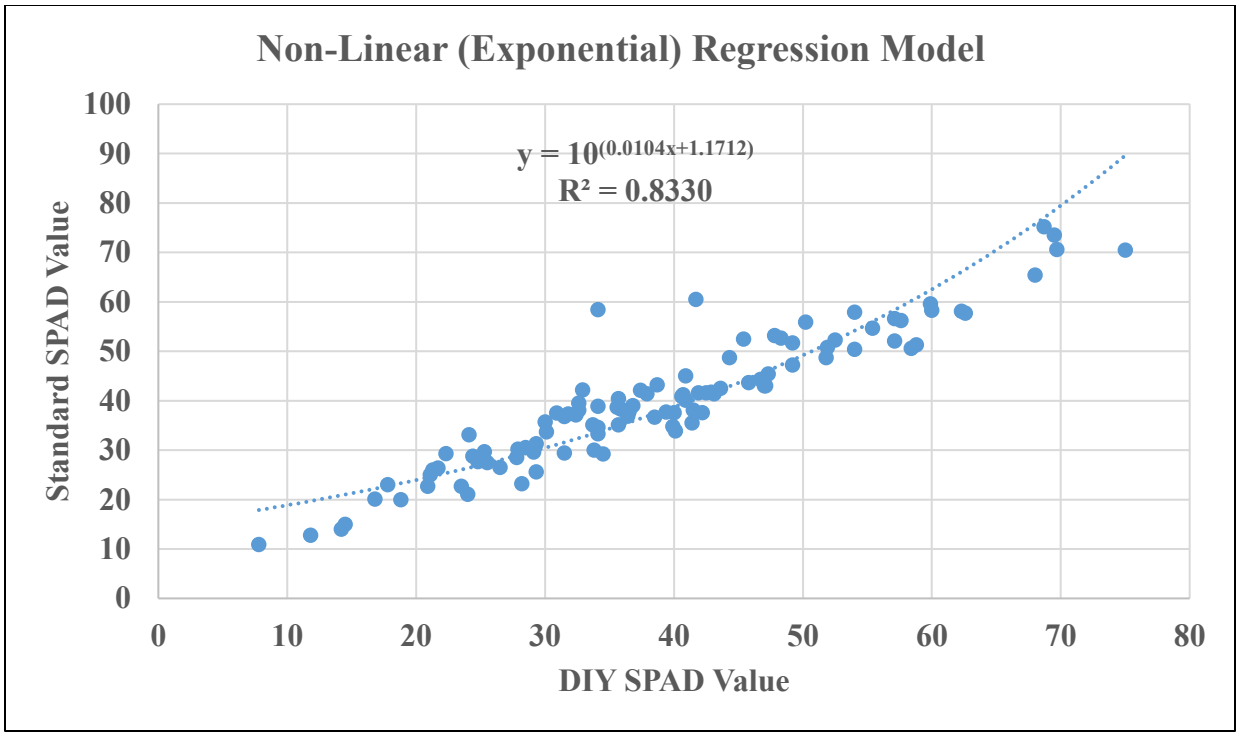


Fig. 20 Validation of Non-Linear (Exponential) Regression Model

Comparison between the SPAD values obtained from the standard SPAD meter, Predicted by linear regression model and Non-Linear (Exponential) Regression Model were shown in fig. 21. Based on their R^2 values of both model Linear Regression Model is used to find the real time SPAD value in DIY SPAD meter.

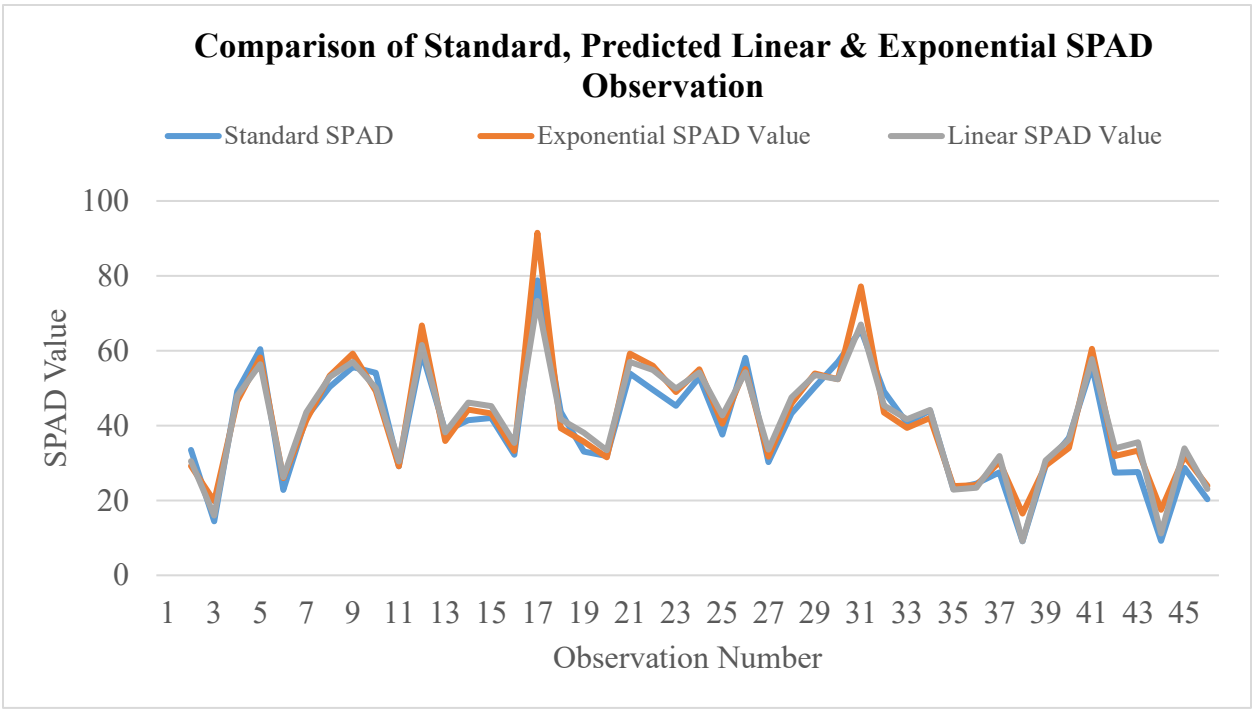


Fig. 21 Comparison Graph of Real, Predicted Linear & Exponential SPAD Values

3.5 Accuracy of SPAD Meter

Accuracy of SPAD meter found by formula mentioned in the section of Validation of the DIY SPAD Meter and shows in fig. 22. Range of DIY SPAD, Standard SPAD and their Accuracy found to be 6.8 to 76, 9.1 to 78.8 and 73.91 to 99.75 %, with an average of 40.69, 40.21 and 91.80 % respectively.

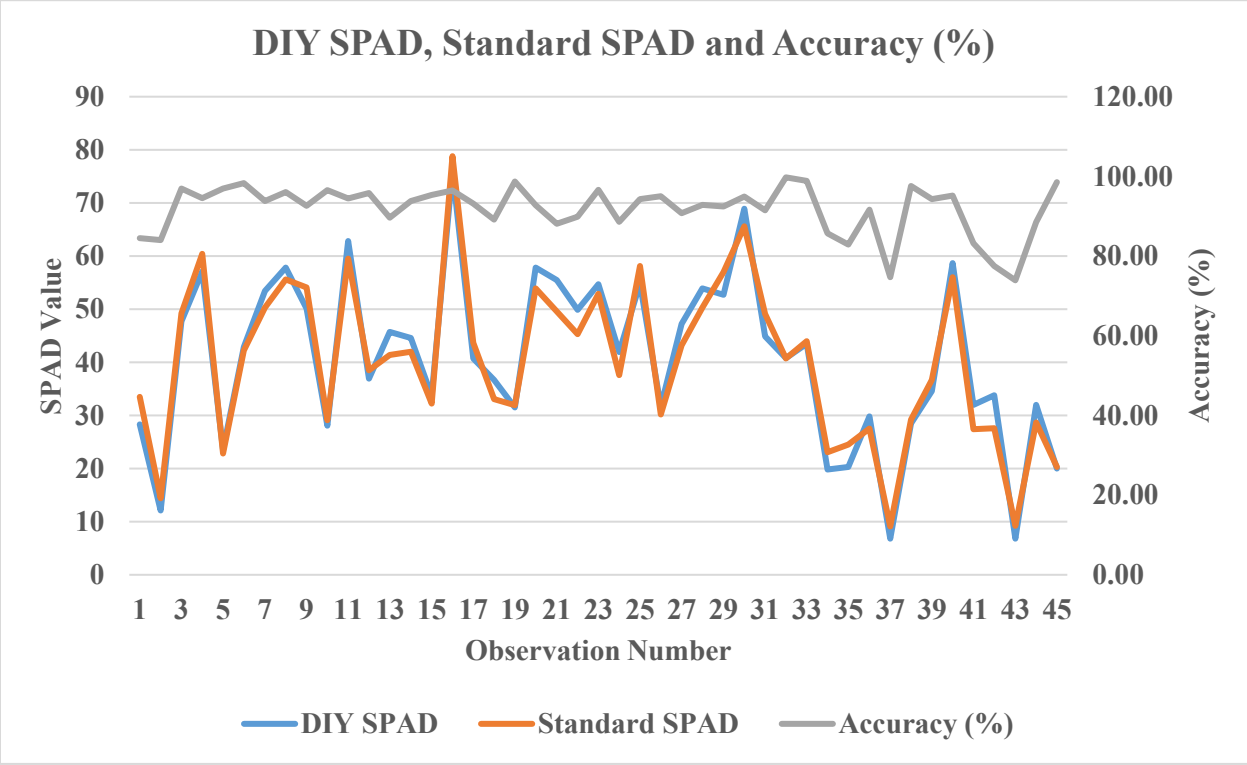


Fig. 22 Accuracy of SPAD Meter

3.6 Error Analysis

The deviations were observed in certain samples (e.g., low SPAD values in Sapota and Maize) may be attributed to,

1) Leaf thickness variation
2) Uneven chlorophyll distribution
3) Sensor sensitivity limitations
4) External light interference
5) Positioning error during measurement

Despite these factors, the error remains within acceptable limits for field applications. These errors were systematic and random in nature but remain within acceptable engineering tolerance limits (<10%).

3.7 Cost estimation

Total cost required to build SPAD meter is illustrate in table 4. Total cost consist of price of electronic component at market price consider and found to be only ₹3,182. This cost as compared with available SPAD meter in market in table 5, it was found to be lowest and affordable.

Table 4. Cost of developed SPAD meter.

Sr. No.	Component	Cost (₹)
1	Arduino Nano	560
2	Arduino Nano Cable	80
3	Light Sensor	509
4	Red LED	3
5	IR LED	10
6	OLED Display (2)	534
7	Push Buttons (2)	12
8	Rocker Switch	15
9	Resistors	6
10	Li-ion Battery (2)	160
11	Charging Module	234
12	Jumper Wires	100
13	Breadboard	45
14	Battery Holder	80
15	Stationery & Connecting Items	134
16	Transportation Charges	550
17	Labour Charges	150
	Total Estimated Cost	**₹3,182**

Table 5. Comparison of Cost of SPAD meter available in market with developed DIY SPAD

Sr. No.	SPAD Meter	Approximate Cost (₹)	Reference
1.	Konica Minolta SPAD-502 Plus	2,29,999	https://www.indiamart.com/proddetail/konica-minolta-spad-502-plus-chlorophyll-meter-26734038612.html?srsltid=AU7gw4XI0_34zFL243JaYYSoFqu9W7WSzDDSxtim7886J1w2s-gDwVwe

Sr. No.	SPAD Meter	Approximate Cost (₹)	Reference
2.	Apogee MC-100 Chlorophyll Meter	2,10,800/-	https://www.indiamart.com/proddetail/apogee-mc-100-chlorophyll-meter-spad-26101920362.html?srsltid=AU7gw4Wf-hUfmqeR45cNiv1A2rCOxlz4EBZX3B9sObV-c7DFgBNakNHF
3.	BR Biochem Plus Chlorophyl Meter with LCD Display and-9.9 to 199.9 SPAD units Measuring Range, BR-CM-502	1,69,999/-	https://www.industrybuying.com/multiparameter-meters-br-biochem-LAB.MUL.142023294
4.	Atleaf CHL Blue Digital Chlorophyll Fluorometer	1,10,000/-	https://www.indiamart.com/proddetail/atleaf-chl-blue-digital-chlorophyll-fluorometer-26733928033.html?srsltid=AU7gw4VWGi3_fuTm8vYdfVRnJSMPj1BMWTbVGqHzXZ9wTn-7PPJ9-E_3
5.	MTech Chlorophyll Meter - MSI0542356 (Digital, Fluorescence, USB)	44.000/-	https://www.indiamart.com/proddetail/chlorophyll-meter-msi0542356-2856796581633.html?pos=5&kwd=digital%20chlorophyll%20analyzer&tags=rk:B||dt:8584|db:172|prc:1|dtp:p||sv:M|rsf:gl|prv:44000|ri:M_B_G250_NP|em:0-|-res:RC2|ktp:N0|stype:attr=1|mtp:S|wc:3|lcf:-1|cq:walsang|qr_nm:gl-gd|cs:20649|com-cf:nl|ptrs:na|mcatc:1|mc:146983|cat:752|qry_typ:P|lang:en|qrd:260927|mrd:260927|prdt:260927|msf:hs|pfen:1|gli:U0G1I0|gc:Digras|ic:Walsang|scw:1|emt:1|v=4|crs=city-landing|r=5
6.	**Developed DIY SPAD Meter**	**3,182**	**Our Developed DIY SPAD Meter**

4. Conclusion

The final calibration equation SPAD = 0.897 × SPADDIY + 5.1487 provided reliable real-time chlorophyll estimation for field applications. Results obtained from developed DIY SPAD meter are

significant by linear regression model with R^2 0.8822 and validation accuracy of 91.86% compared with the standard SPAD-502 meter. DIY SPAD meter found to be cost effective with development cost of Rs.3182 as compared to SPAD 502 meter. Provides non-destructive chlorophyll estimation which supporting precision agriculture, crop monitoring, and fertilizer management.

CONFLICT OF INTEREST

"The authors declare no conflict of interest."

DATA AVAILABILITY STATEMENT

“Data will be made available on request”

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