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Real-Time Monitoring and Sonification of Mung Bean (Vigna radiata) Bioelectrical Responses to LED Light Spectra Using an ESP32-Based Embedded System

Eddy Lybrech Talakua[1]*, Eko Haris Siswanto[2], Mahesa Sangga Bhuwana[3], Erwin Dhaniswara[4]
[1,2,3,4] Department of Electronics Engineering, Faculty of Engineering, Universitas Widya Kartika, Surabaya 60113, Indonesia

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ABSTRACT

The advancement of indoor farming as a solution to limited agricultural land has driven the use of Light Emitting Diodes (LEDs) as artificial lighting sources capable of controlling plant growth environments. Variations in LED light spectra are known to influence plant physiological activities, including changes in bioelectrical signals that can serve as early indicators of plant physiological conditions. However, most bioelectrical monitoring systems still present information in numerical or graphical formats, which are less intuitive for direct real-time interpretation. This study presents a pilot investigation of the effect of four LED light spectra (red, blue, green, and white) on the bioelectrical responses of a mung bean plant (Vigna radiata), together with the development of an ESP32-based embedded system that performs real-time bioelectrical signal acquisition, timestamped data logging, and Parameter Mapping Sonification of the signals into musical notes. The system integrates bioelectrical electrodes, an AD8232 signal-conditioning module, an ESP32 microcontroller, a DS3231 RTC module, a microSD card, and a DFPlayer Mini audio module. Measurements were repeated across four trials for each LED spectrum on a single test plant. Blue and white LEDs produced the highest mean Vrms (1.431 V), red LED produced the highest average Vpp (0.448 V), and green LED produced the lowest average Vpp (0.311 V); trial-to-trial variability (SD up to 0.18 V for Vpp) indicates that further biological replication is needed before the spectral effect can be generalized. The system successfully performed real-time acquisition, logging, and sonification, converting bioelectrical voltage into 28 distinct musical notes. These preliminary results indicate that the proposed embedded architecture is technically feasible for auditory representation of plant bioelectrical dynamics and may support the future development of non-destructive, smart-agriculture monitoring tools; confirming the generality of the LED-spectrum effect and the perceptual benefit of sonification will require larger biological replication and a formal user study.

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Corresponding Author:
Eddy Lybrech Talakua,
Universitas Widya Kartika, Sutorejo Prima Utara II /1, Surabaya 60113, Indonesia
Email: eddytalakua@widyakartika.ac.id Orcid ID : 0009-0004-7328-2237

1. INTRODUCTION

The development of precision agriculture and indoor farming has accelerated the utilization of sensor technologies, the Internet of Things (IoT), and intelligent systems to enhance crop cultivation efficiency through real-time physiological monitoring. One rapidly advancing technology is the use of Light Emitting Diodes (LEDs) as artificial lighting sources, owing to their high energy efficiency, long operational life, and ability to emit specific light spectra that can be tailored to plant physiological requirements [1], [6], [15]. Numerous studies have demonstrated that variations in LED light spectra—particularly red, blue, green, and

white—exert differential effects on photosynthesis, chlorophyll synthesis, stomatal opening, biomass accumulation, and overall crop productivity [1], [4]–[6], [15], [21]–[23].

Beyond influencing plant growth, changes in light spectra also affect bioelectrical activity within plant tissues. Bioelectrical activity refers to changes in electrical potential resulting from ion movement across cell membranes in response to various environmental stimuli, including light intensity, spectral composition, temperature, humidity, and mechanical conditions [7], [31], [32]. These bioelectrical responses emerge earlier than observable morphological changes, making them potentially valuable as early indicators of plant physiological status and supporting non-destructive monitoring systems [3], [13], [14], [34].

Recent advances in plant electrophysiology research indicate that plant bioelectrical signals can be employed to detect environmental stress, changes in growth conditions, and responses to specific treatments. Li et al. [13] reported that enhanced bioelectrical signal acquisition quality enables more sensitive detection of mechanical responses in plants under dark conditions. Garcia-Menchaca et al. [3] utilized bioelectrical signals from hydroponic strawberry plants combined with machine learning techniques to identify plant response characteristics to optical stimulation. Furthermore, Stolarz et al. [14] integrated plant bioelectrical analysis with Artificial Intelligence (AI) and time-lapse imaging as a novel approach in precision agriculture systems. These findings collectively indicate that bioelectrical signals hold substantial potential as real-time sources of plant physiological information.

Concurrently, the development of sonification methods has opened new opportunities for scientific data presentation. Sonification is the technique of transforming data into auditory information, enabling changes in a given parameter to be perceived through sound [16], [18]. This approach is increasingly employed as a complement to data visualization, as it can enhance the speed of interpretation of continuously changing data [17], [18], [24]. In the plant domain, Dai et al. [2] developed a sonification system for aquatic plant photosynthesis activity as a medium for human-plant interaction. Other studies have also explored the sonification of plant bioelectrical signals for artistic and educational purposes [25]–[27]. Nevertheless, most sonification research remains focused on visualization or data communication aspects, while the implementation of sonification for plant bioelectrical signals on embedded systems remains very limited.

Based on the literature review, two main research gaps are identified. The first is a scientific gap: although the effect of LED spectra on plant growth is well documented [1], [4]–[6], [15], [21]–[23], its effect on plant bioelectrical signal characteristics—particularly when compared across colour conditions using a standardized acquisition protocol—remains comparatively underexplored [7], [31], [32]. The second is an engineering gap: existing bioelectrical monitoring approaches typically depend on external computers or offline analysis for signal interpretation [3], [13], [14], and reported sonification work has mostly targeted visualization, artistic, or educational contexts rather than a fully self-contained, low-cost embedded device capable of simultaneous acquisition, timestamped storage, and real-time auditory representation [2], [16], [18], [24]–[27].

To address these two gaps, this study develops a monitoring system for the effect of LED light spectra on plant bioelectrical signals using an ESP32 microcontroller [8], integrating an AD8232 module as a bioelectrical signal conditioner [10], a DS3231 RTC module for timestamping [11], a microSD card for data storage, and a DFPlayer Mini for audio output [12]. The system is designed to acquire bioelectrical signals from a mung bean plant (Vigna radiata) in real time during exposure to red, blue, green, and white LED light spectra. The acquired bioelectrical data are then processed using the Parameter Mapping Sonification method [16] to represent changes in signal characteristics as musical scales that are easily perceivable by users.

It should be acknowledged that the individual hardware components used in this study — the ESP32 microcontroller, SD-card data logging, and RTC-based timestamping — are widely available and technically well established, and are not in themselves novel. The contribution of this work is therefore not a new sensing principle, but rather (1) an empirical, spectrum-resolved characterization of mung bean bioelectrical response magnitude (Vrms, Vpp, and mean voltage) under four controlled LED light conditions, and (2) a fully self-contained embedded pipeline that performs bioelectrical acquisition, timestamped storage, and Parameter Mapping Sonification entirely on-device and in real time, without dependence on an external computer for interpretation — a combination that, to the best of the authors' knowledge, has not previously been reported for plant bioelectrical monitoring [2], [3], [13], [14]. The novelty of this study is therefore best characterized as an applied engineering integration together with a preliminary empirical dataset, rather than a fundamental scientific discovery.

This study aims to: (1) obtain a preliminary empirical characterization of the effect of LED light spectrum variation on the bioelectrical signal characteristics of a mung bean plant; (2) design and implement an ESP32-based bioelectrical monitoring system capable of real-time acquisition, timestamping, and data storage; and (3) implement the Parameter Mapping Sonification method as a medium for auditory representation of changes in plant bioelectrical signals. The results of this study are expected to contribute to the development of smart agriculture technologies, non-destructive plant physiological monitoring systems, and to serve as a foundation for future IoT-based and AI-based plant bioelectronic systems [3], [14], [34].

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2. METHOD

2.1 Research Design

This study employs an experimental method with a quantitative approach to analyze the effect of variations in LED light spectra on the bioelectrical signal characteristics of a mung bean plant (Vigna radiata L.). Because the study uses a single plant specimen (Section 2.3), it is best characterized as a pilot / preliminary experiment intended to establish technical feasibility and to generate preliminary effect estimates, rather than to provide a statistically generalizable conclusion about the species; this scope is discussed further in Section 3.9. The developed system consists of three main stages: bioelectrical signal acquisition, storage of measurement data, and sonification of signals into musical scale representations in real time [16]. The overall architecture of these three stages is illustrated in the system block diagram in Figure 1.

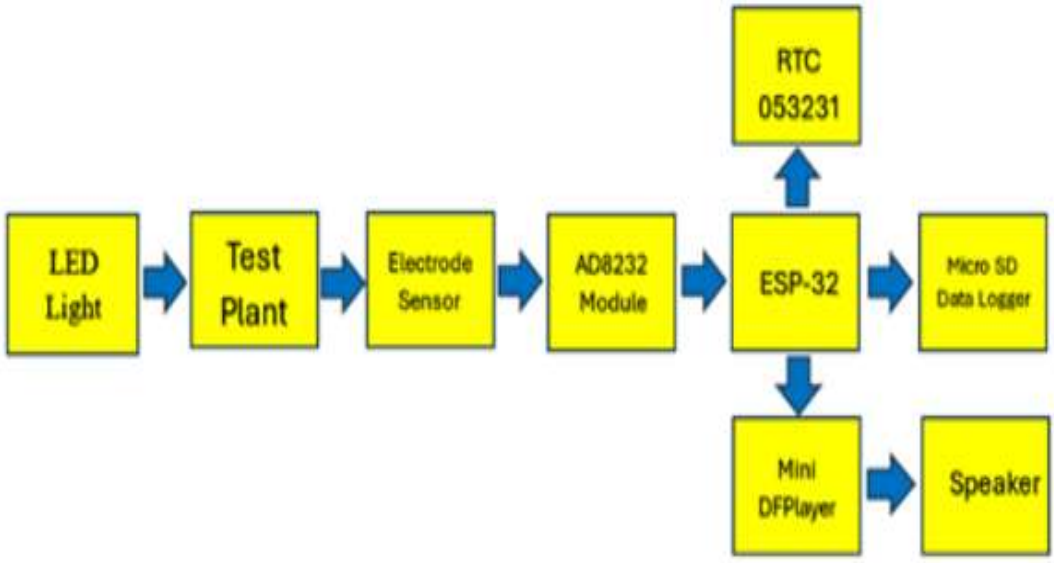

Figure 1. System block diagram

2.2 Monitoring and Sonification System (ESP32 System)

The developed system uses an ESP32 microcontroller [8] as the processing unit to read, process, store, and convert plant bioelectrical signals into sound representations through the sonification method [16], [18]. During LED illumination, the ESP32 monitors changes in bioelectrical signals detected by electrodes attached to the leaves and stems of the plant. The complete operating logic of this process, from signal reading to sonified output, is presented in the flowchart in Figure 2.

Figure 2. Flowchart of the ESP32-based plant bioelectrical monitoring system

When the plant receives LED illumination, electrodes attached to the leaves and stems detect bioelectrical signals as physiological responses to changes in light spectra [7], [31]. These very low-amplitude signals are amplified and filtered using the AD8232 module [10] before being converted into digital data by the ESP32's ADC. The measurement data are then stored on a microSD card along with timestamps from the DS3231 RTC module [11] to ensure that each data point has accurate time information. The physical realization of this hardware setup is shown in Figure 3.

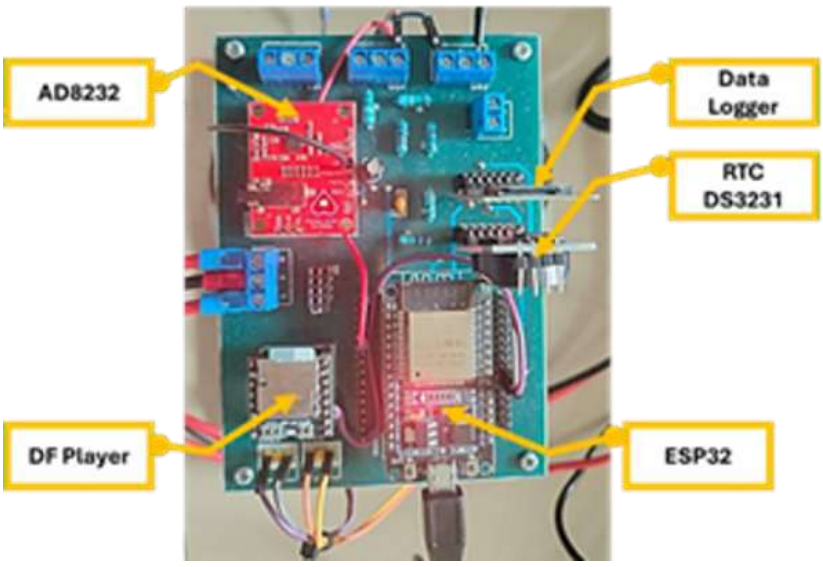

Figure 3. Hardware implementation of the monitoring system for the effect of LED light spectra on plant bioelectrical signals based on ESP32

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Subsequently, the voltage values are mapped into 28 musical notes (C3–B6) using the Parameter Mapping Sonification method [16], [18]. The mapping results are sent by the ESP32 to the DFPlayer Mini [12] for playback through a speaker, enabling changes in bioelectrical signals to be heard as sound representations. The entire process of acquisition, storage, and sonification occurs in real time during testing, while all data are also stored on the microSD card for further analysis.

2.3 Data Collection Method

Data collection was performed on a single mung bean plant subjected to four repeated trials for each of the four LED light spectra (red, blue, green, white), applied in the fixed sequence summarized in Table 1. Because only one biological specimen was used, the four trials constitute technical (within-plant) replicates rather than independent biological replicates; this constraint, and its implications for generalizability, is discussed in Section 3.9. Each LED exposure lasted 10 minutes and was followed by a rest (baseline-recovery) interval of the same duration, during which no LED illumination was applied.

The 10-minute duration was adopted based on a preliminary observation that the plant's bioelectrical signal returned to a stable baseline within this interval, consistent with the recovery behaviour reported for plant electrical signals following stimulus removal [13]. The same 8-segment exposure/rest sequence shown in Table 1 was repeated identically across all four trials; consequently, order or fatigue effects on the plant's baseline cannot be fully ruled out (see Section 3.9).

Table 1. Data Collection Protocol (the 8-segment sequence below was repeated for Trials 1–4)

Segment	Condition	Duration
1	Red LED exposure	10 min
2	Rest (baseline recovery)	10 min
3	Blue LED exposure	10 min
4	Rest (baseline recovery)	10 min
5	Green LED exposure	10 min
6	Rest (baseline recovery)	10 min
7	White LED exposure	10 min
8	Rest (baseline recovery)	10 min

2.4 Data Analysis

Data analysis was performed to obtain a preliminary characterization of the effect of LED light spectrum variation on the bioelectrical signal of the mung bean plant. The measurement data were grouped according to LED light spectrum treatment and analyzed using the following descriptive parameters:

- Mean Voltage (VMean)
- Root Mean Square (RMS) Voltage (Vrms)
- Peak-to-Peak Voltage (Vpp)

For each LED spectrum, the mean and standard deviation (SD) across the four trials were computed and are reported in Table 8. As the four trials are technical replicates from a single plant rather than independent biological replicates, these statistics are descriptive only; no inferential hypothesis testing (e.g., ANOVA) was performed, and the SD values are reported primarily to convey trial-to-trial variability [1], [6], [15].

2.5 Sonification Method

The sonification stage was conducted using the Parameter Mapping Sonification approach [16], [18]. The characteristic values of bioelectrical signals were mapped into several levels of musical notes so that changes in plant physiology could be represented as sound [24]–[27].

The higher the bioelectrical parameter value obtained, the higher the resulting note frequency. Conversely, a decrease in bioelectrical activity produces notes with lower frequencies [16].

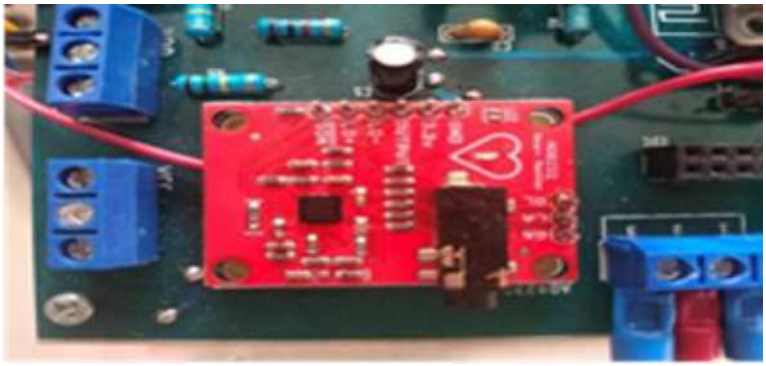

Figure 4. Implementation of the sonification system using DFPlayer Mini and speaker

Figure 5. Implementation of the bioelectrical sensor using the AD8232 module

This approach enables users to be alerted to changes in plant physiological conditions without having to read measurement graphs. The acquired bioelectrical data are converted into musical scales using the parameter mapping sonification method based on predetermined voltage ranges [16], [18]; the extent to which this is perceived as intuitive by end users was not evaluated in this study (Section 3.9).

2.6 Software

The system software was developed using the Arduino IDE [9] with the C/C++ programming language. The program on the ESP32 consists of several main functions:

- Initialization of all hardware components.
- Reading of analog data from the AD8232 [10].
- Initial data filtering.
- Time recording using the RTC [11].
- Data storage to the microSD card.
- Calculation of signal parameters.
- Conversion of parameters into musical notes [16].
- Sending of audio commands to the DFPlayer Mini [12].

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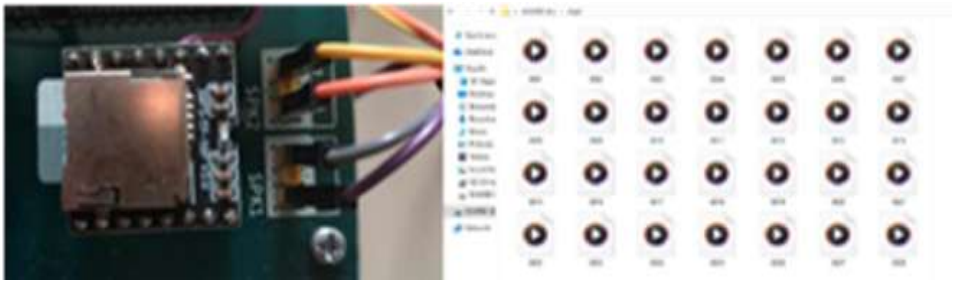

Figure 6. System flowchart

3. RESULTS AND DISCUSSION

3.1 System Setting and Data Acquisition

At this stage, all components were assembled, integrated, and tested to ensure they functioned according to the research requirements. The constructed system consisted of a bioelectrical sensor, an ESP32 microcontroller [8], a sonification system using the DFPlayer Mini [12] and a speaker, and a data storage system using the DS3231 RTC [11] and a microSD data logger. Testing and data acquisition were divided into several stages:

- Performance testing of each individual circuit.
- Testing and data acquisition of the bioelectrical sensor.
- Testing and data acquisition of the sonification system.
- Testing and data acquisition of the data storage system.
- Testing and data acquisition of the system under various LED light spectra.

3.2 Performance Testing of Individual Circuit

Testing was conducted by observing the ESP32's ability to read sensor data, communicate with the RTC and microSD, and control the DFPlayer Mini [8]–[12].

Table 2. Results of Individual Circuit Performance Testing

Test Parameter	Result	Status
Sensor Reading	Voltage value changed when sensor was touched	Successful
RTC & MicroSD Communication	Data logger stored data with correct time and voltage values	Successful
DFPlayer Communication	Speaker produced sounds with various musical notes	Successful

3.3 Bioelectrical Sensor Testing and Data Acquisition

The bioelectrical sensor was implemented using the AD8232 module [10] combined with clip electrodes attached to the leaves and stems of the mung bean plant [7], [30].

Figure 7. Electrode placement on the plant

The test results showed that the AD8232 module was capable of detecting changes in plant bioelectrical signals and producing voltage outputs readable by the ESP32. During testing, the acquired signals exhibited value changes corresponding to plant conditions and applied treatments [10], [33].

3.4 Sonification System Testing and Data Acquisition

The sonification process was carried out using the parameter mapping sonification method [16], [18], mapping bioelectrical voltage values into several predetermined note levels. Each voltage range had a different note representation, allowing changes in plant bioelectrical activity to produce audible changes in pitch [24]–[27].

Table 3. Mapping of Bioelectrical Voltage Range to Sonification Musical Notes

No.	Voltage Range (V)	Note
1	0 – <1.309	C3
2	1.309 – <1.318	D3
3	1.318 – <1.327	E3
4	1.327 – <1.336	F3
5	1.336 – <1.345	G3
6	1.345 – <1.354	A3
7	1.354 – <1.363	B3
8	1.363 – <1.372	C4
9	1.372 – <1.381	D4
10	1.381 – <1.390	E4
11	1.390 – <1.399	F4
12	1.399 – <1.408	G4
13	1.408 – <1.417	A4
14	1.417 – <1.426	B4
15	1.426 – <1.435	C5
16	1.435 – <1.444	D5
17	1.444 – <1.453	E5
18	1.453 – <1.462	F5
19	1.462 – <1.471	G5
20	1.471 – <1.480	A5
21	1.480 – <1.489	B5
22	1.489 – <1.498	C6
23	1.498 – <1.507	D6
24	1.507 – <1.516	E6
25	1.516 – <1.525	F6
26	1.525 – <1.534	G6
27	1.534 – <1.543	A6
28	≥ 1.543	B6

The test results showed that the DFPlayer Mini was able to receive commands from the ESP32 correctly and play audio files according to the predetermined mapping [12]. The speaker produced sufficiently clear sound, allowing note differences to be distinguished by the researchers during testing. Note changes occurred automatically in response to changes in bioelectrical values read by the monitoring system [16], [18]; whether these note differences are readily distinguishable by naive listeners was not formally tested (Section 3.9).

3.5 Data Storage System Testing and Data Acquisition

Testing was conducted by activating the monitoring system and observing whether sensor reading data were automatically stored on the microSD card along with corresponding time information [11].

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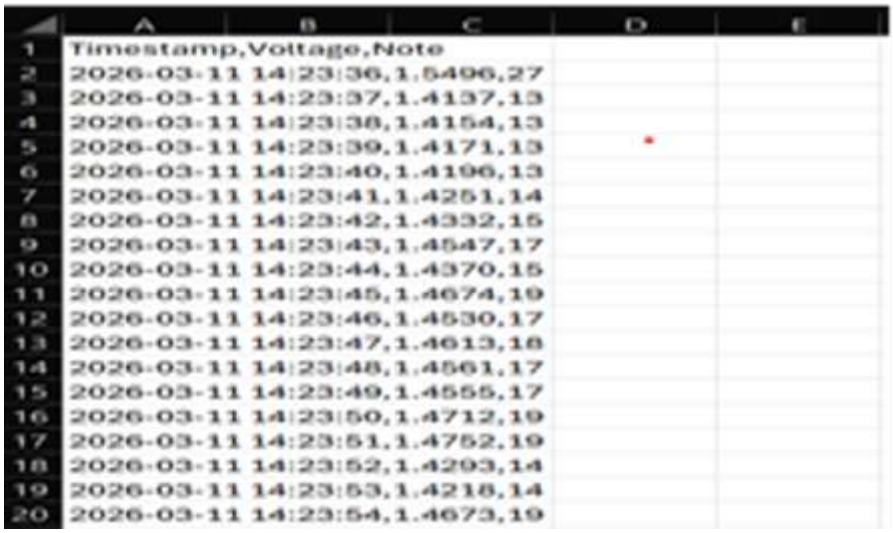

	A	B	C	D	E
1	Timestamp,Voltage,Note				
2	2026-03-11 14:23:36,1.5496,27				
3	2026-03-11 14:23:37,1.4137,13				
4	2026-03-11 14:23:38,1.4154,13				
5	2026-03-11 14:23:39,1.4171,13				
6	2026-03-11 14:23:40,1.4196,13				
7	2026-03-11 14:23:41,1.4251,14				
8	2026-03-11 14:23:42,1.4332,15				
9	2026-03-11 14:23:43,1.4547,17				
10	2026-03-11 14:23:44,1.4370,15				
11	2026-03-11 14:23:45,1.4674,19				
12	2026-03-11 14:23:46,1.4530,17				
13	2026-03-11 14:23:47,1.4613,18				
14	2026-03-11 14:23:48,1.4561,17				
15	2026-03-11 14:23:49,1.4555,17				
16	2026-03-11 14:23:50,1.4712,19				
17	2026-03-11 14:23:51,1.4752,19				
18	2026-03-11 14:23:52,1.4293,14				
19	2026-03-11 14:23:53,1.4218,14				
20	2026-03-11 14:23:54,1.4673,19				

Figure 8. Screenshot of data storage results on the microSD card

The test results showed that the DS3231 RTC module provided accurate and stable time information throughout the testing period [11]. In addition, the microSD module successfully stored all measurement data without data loss or recording errors.

3.6 System Testing and Data Acquisition Under Various LED Light Spectra

Testing was conducted using four light color variations—red, blue, green, and white—applied sequentially according to the protocol in Table 1 [1], [4]–[6], [15], [21]–[23]. As noted in Section 2.3, all trials were obtained from a single plant specimen; the values below should therefore be read as preliminary, within-plant observations.

3.6.1 Bioelectrical test results for red LED

The measurement results showed that during red light exposure, plant bioelectrical signals underwent observable changes reflected in the voltage variations recorded by the monitoring system.

Table 4. Bioelectrical Measurement Results for Red LED

Trial	Vrms (V)	Vpp (V)	Mean (V)
1	1.430	0.316	1.428
2	1.431	0.461	1.429
3	1.424	0.573	1.423
4	1.426	0.440	1.425

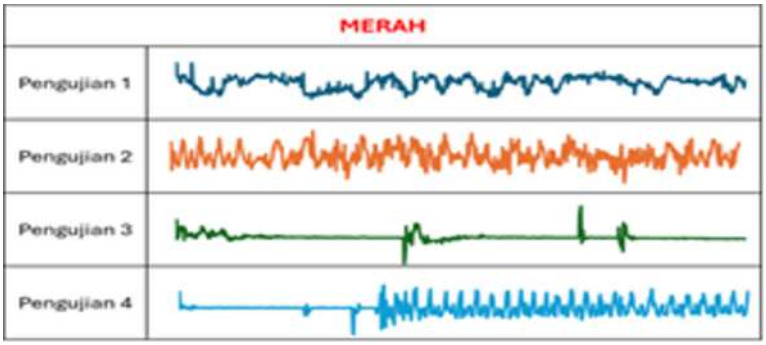

Figure 9. Graph of plant bioelectrical response under red LED

3.6.2 Bioelectrical test results for blue LED

The measurement results showed that during blue light exposure, plant bioelectrical signals underwent observable changes reflected in the voltage variations recorded by the monitoring system [1], [6].

Table 5. Bioelectrical Measurement Results for Blue LED

Trial	Vrms (V)	Vpp (V)	Mean (V)
1	1.433	0.215	1.433
2	1.433	0.354	1.432
3	1.431	0.490	1.429
4	1.428	0.643	1.428

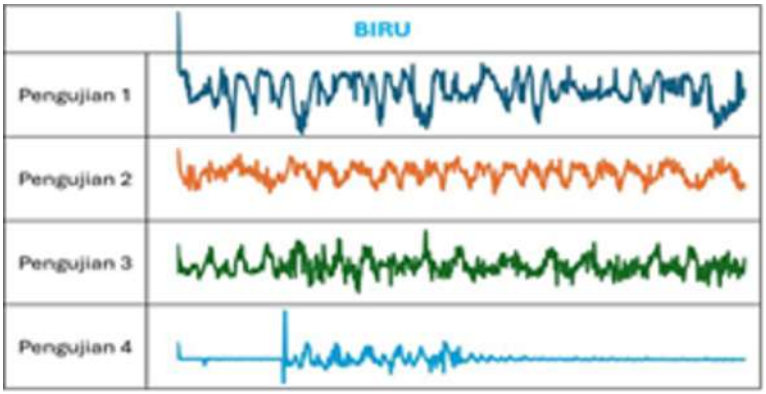

Figure 10. Graph of plant bioelectrical response under blue LED

3.6.3 Bioelectrical test results for green LED

The measurement results showed that during green light exposure, plant bioelectrical signals underwent observable changes reflected in the voltage variations recorded by the monitoring system [4], [5].

Table 6. Bioelectrical Measurement Results for Green LED

Trial	Vrms (V)	Vpp (V)	Mean (V)
1	1.434	0.214	1.434
2	1.422	0.278	1.421
3	1.424	0.275	1.424
4	1.425	0.479	1.425

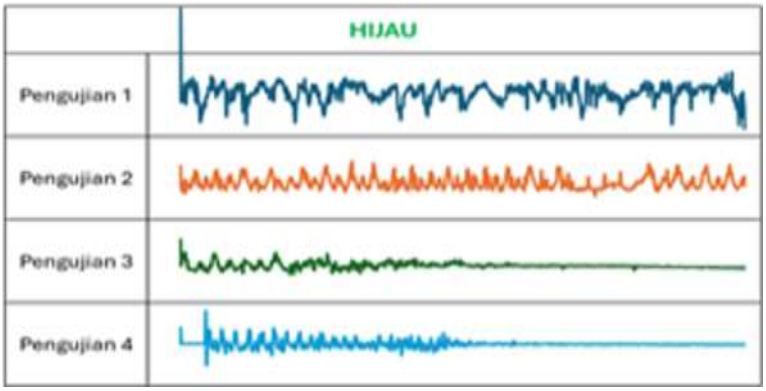

Figure 11. Graph of plant bioelectrical response under green LED

3.6.4 Bioelectrical test results for white LED

The measurement results showed that during white light exposure, plant bioelectrical signals underwent observable changes reflected in the voltage variations recorded by the monitoring system [1], [15].

Table 7. Bioelectrical Measurement Results for White LED

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Trial	Vrms (V)	Vpp (V)	Mean (V)
1	1.439	0.480	1.437
2	1.429	0.400	1.428
3	1.433	0.268	1.433
4	1.424	0.162	1.424

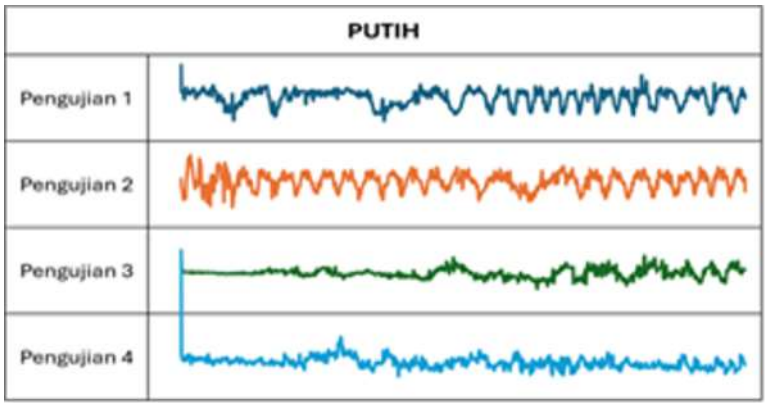

Figure 12. Graph of plant bioelectrical response under white LED

3.7 System Performance Analysis

3.7.1 Analysis of plant bioelectrical test results

The plant bioelectrical testing produced data corresponding to the applied LED colors. From each LED and each trial, Vrms, Vpp, and VMean values were obtained, allowing the calculation of the mean and standard deviation (SD) for each LED color as follows:

Table 8. Average (Mean ± SD) Bioelectrical Test Results for All LEDs, n = 4 Trials per LED

LED	Vrms (V)	Vpp (V)	VMean (V)
Red	1.428 ± 0.003	0.448 ± 0.105	1.426 ± 0.003
Blue	1.431 ± 0.002	0.425 ± 0.183	1.430 ± 0.002
Green	1.426 ± 0.005	0.311 ± 0.115	1.426 ± 0.006
White	1.431 ± 0.006	0.328 ± 0.141	1.430 ± 0.006

Based on the test results for the four LED light spectra, the following preliminary observations were made:

- Blue and white LEDs produced the highest mean Vrms and VMean values (1.431 V and 1.430 V respectively), suggesting that average plant bioelectrical activity may be higher under these spectra [1], [6], [15].
- Red LED produced the highest average Vpp value (0.448 V), suggesting the greatest fluctuation in bioelectrical signals under this condition, though the associated SD (0.105 V) indicates considerable trial-to-trial variability [7], [31].
- Green LED produced the lowest average Vpp value (0.311 V), suggesting comparatively more stable bioelectrical responses; again, the SD (0.115 V) shows this trend is not yet statistically confirmed [4], [5].
- Overall, the four LED spectra produced different average response magnitudes and different degrees of trial-to-trial variability; these results are preliminary indicators of spectral dependency rather than confirmed effects, given the single-specimen design (Section 3.9) [1], [6], [15], [21]–[23].

3.7.2 Analysis of sonification test results

The sonification process in this study employed the parameter mapping sonification method [16], [18], converting plant bioelectrical voltage values into 28 musical notes based on predetermined voltage ranges. The test results showed that the system was capable of producing note changes corresponding to changes in bioelectrical signals during testing with red, blue, green, and white LED spectra, consistent with the sampling interval and latency reported in Section 3.2. The note variations observed in each trial indicate that plant bioelectrical responses are dynamic in nature [7], [31]. The sonification system thus functioned as designed at a technical level, automatically converting changes in plant bioelectrical signals into sound representations [16], [18], [24].

3.7.3 System performance analysis

Based on the implementation and test results, the ESP32-based plant bioelectrical monitoring system [8] operated according to the design specifications. The AD8232 sensor successfully read bioelectrical signals [10], the DS3231 RTC module [11] and microSD card stored measurement data, and the DFPlayer Mini [12] produced audio output based on the processed data [16].

The testing demonstrated that the processes of reading, data storage, and sonification occurred automatically, with all system components functioning reliably throughout the testing period [33]. Overall, the system fulfilled its intended engineering objectives and can be used as an ESP32-based mung bean plant bioelectrical monitoring platform equipped with data storage and musical-scale sonification features [8], [10]–[12], [16], [18].

3.8 Limitations

The following limitations should be considered when interpreting the results of this study:

- Single biological specimen: all measurements were obtained from one mung bean plant, with four within-plant technical replicate trials per LED spectrum. This design does not provide biological replication, so the observed spectral differences should be regarded as preliminary trends rather than statistically generalizable conclusions about Vigna radiata as a species. Confirming a generalizable LED-spectrum effect requires independent biological replicates (multiple plants) analyzed with an appropriate inferential test (e.g., ANOVA with post-hoc comparison).
- No formal statistical hypothesis testing: given the limited number of technical replicates and the absence of biological replication, only descriptive statistics (mean ± SD, Table 8) are reported; no test of statistical significance was performed.
- Uncontrolled light intensity (PPFD): photosynthetic photon flux density was not independently measured or equalized across the four LED sources in this study. Because bioelectrical responses can be influenced by light intensity as well as spectral composition [1], [6], [15], part of the observed differences between LED colors may reflect intensity variation between light sources rather than spectral composition alone. Future work should measure and equalize PPFD across all light conditions.
- Fixed trial order: the four LED conditions were applied in the same sequence in every trial (Table 1), so order or fatigue effects on the plant's bioelectrical baseline cannot be ruled out. Randomizing the LED sequence across trials is recommended in future work.
- No formal user evaluation of the sonification output: the sonification subsystem was verified to function correctly at a technical level (Sections 3.4 and 3.7.2)—correctly mapping voltage ranges to musical notes and producing audible output on cue—but no usability test, listening experiment, or note-recognition study with human participants was conducted. Claims that the auditory representation is "intuitive" or enables users to "perceive variations" should therefore be read as a statement of the system's design goal and demonstrated technical capability, not as an empirically validated perceptual outcome. A structured user study (e.g., a note-discrimination accuracy test or a System Usability Scale questionnaire with a defined number of participants) is recommended as a direct next step.

4. CONCLUSION

Based on the experimental results and system performance evaluation obtained from this pilot study, several conclusions can be drawn. Variations in LED light spectra were associated with distinct bioelectrical response patterns in the tested mung bean plant (Vigna radiata): blue and white LEDs produced the highest average bioelectrical activity (Vrms = 1.431 V), red LED showed the largest average signal fluctuation (Vpp = 0.448 ± 0.105 V), and green LED showed comparatively more stable responses (Vpp = 0.311 ± 0.115 V); as all trials were conducted on a single specimen, these findings should be treated as preliminary indications of spectral dependency rather than confirmed, generalizable effects, and validation with additional biological replicates and controlled light intensity is required. The ESP32-based monitoring system successfully performed acquisition, processing, and timestamped storage of bioelectrical signals without data loss across all testing sessions, and the integration of the AD8232, DS3231 RTC, and microSD modules on a single embedded platform functioned reliably throughout testing. The Parameter Mapping Sonification subsystem correctly converted bioelectrical signal values into 28 distinct musical notes and produced audible output automatically in response to signal changes, demonstrating the technical feasibility of the proposed auditory representation approach, although whether this representation is, in practice, intuitive or perceptually useful to end users was not evaluated in this study and remains an important direction for future work. Overall, this research contributes an applied engineering integration and a preliminary empirical dataset toward the development of smart

agriculture systems [3], [14] and non-destructive plant monitoring technologies [34], [35]; future work should prioritize biological replication with appropriate statistical analysis, controlled light-intensity (PPFD) conditions, a randomized trial sequence, and a formal user evaluation of the sonification output.

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REFERENCES

[1] V. Cavallaro and R. Muleo, "The Effects of LED Light Spectra and Intensities on Plant Growth," Plants, vol. 11, no. 15, p. 1911, Jul. 2022, doi: 10.3390/plants11151911.
[2] Y. Dai, A. F. Blackwell, and J. Vines, "Sonifying Aquatic Plant Photosynthesis: A Music Generation System for Everyday Engagement and Care," in Companion Publication of the 2025 ACM Designing Interactive Systems Conference, Funchal, Portugal, Jul. 2025, pp. 452–455, doi: 10.1145/3715668.3736347.
[3] L. Garcia-Menchaca, J. A. Pérez-Ortiz, A. Hernández-Aguirre, and E. R. Palacios-Hernández, "Early-Stage Research to Characterize the Electrical Signal of Optically Stimulated Hydroponic Strawberries Using Machine Learning Techniques," Engineering Proceedings, vol. 87, no. 1, p. 44, Apr. 2025, doi: 10.3390/engproc2025087044.
[4] D. I. Lestari, N. Kurniawati, and A. S. Putra, "Pengaruh Spektrum Cahaya terhadap Perkecambahan Kacang Hijau (Vigna radiata)," Jurnal Penelitian Fisika dan Terapannya (JUPITER), vol. 3, no. 1, pp. 11–16, 2021, doi: 10.31851/jupiter.v3i1.5986.
[5] Rosyida, A. M. Hariri, and A. Nugroho, "Efek Cahaya LED Merah dan Biru pada Pertumbuhan, Hasil dan Kandungan Klorofil Tanaman Pakcoy (Brassica chinensis L.) dalam Growbox," AGROMIX, vol. 13, no. 2, pp. 168–174, 2022, doi: 10.35891/agx.v13i2.3028.
[6] S. Sena, A. Chatterjee, S. Ghosh, and S. Roy, "Light Emitting Diode (LED) Lights for the Improvement of Plant Performance and Production: A Comprehensive Review," Current Research in Biotechnology, vol. 7, p. 100184, 2024, doi: 10.1016/j.crbiot.2024.100184.
[7] A. G. Volkov, Plant Electrophysiology: Signaling and Responses. New York, NY, USA: Springer, 2012.
[8] Espressif Systems, ESP32 Series Datasheet, Version 5.0. Shanghai, China: Espressif Systems, 2024.
[9] Arduino, Arduino IDE Documentation. Somerville, MA, USA: Arduino, 2024.
[10] Analog Devices, AD8232 Heart Rate Monitor Front End Datasheet. Norwood, MA, USA: Analog Devices, 2024.
[11] Analog Devices, DS3231 Extremely Accurate I²C-Integrated RTC/TCXO/Crystal Datasheet. Norwood, MA, USA: Analog Devices, 2018.
[12] DFRobot, DFPlayer Mini MP3 Player Module Datasheet. Shanghai, China: DFRobot, 2024.
[13] Y. Li, X. Zhang, H. Wang, and L. Chen, "Early Detection of Dark-Affected Plant Mechanical Responses Using Enhanced Electrical Signals," Sensors, vol. 24, no. 3, pp. 1–15, 2024.
[14] M. Stolarz, K. Dziubinska, and M. Zawadzki, "Integration of Plant Electrophysiology and Time-Lapse Video Analysis via Artificial Intelligence for Precision Agriculture," Plants, vol. 14, no. 2, pp. 1–18, 2025.
[15] H. Z. Rihan, M. Aldarkazali, and M. P. Fuller, "The Impact of LED Lighting Spectra in a Plant Factory on Growth, Physiological Traits and Essential Oil Content of Lemon Balm (Melissa officinalis L.)," Horticulturae, vol. 8, no. 8, p. 714, 2022, doi: 10.3390/horticulturae8080714.
[16] T. Hermann, A. Hunt, and J. G. Neuhoff, The Sonification Handbook. Berlin, Germany: Logos Publishing House, 2011.
[17] L. Bornmann, "The Sound of Science: Data Sonification Has Emerged as a Possible Alternative to Data Visualization," Quantitative Science Studies, vol. 5, no. 3, pp. 697–703, 2024.
[18] K. Enge et al., "Open Your Ears and Take a Look: A State-of-the-Art Report on the Integration of Sonification and Visualization," Computer Graphics Forum, vol. 43, no. 3, 2024.
[19] P. A. Gloor, "Endogenous Circadian Rhythms in Plant Bioelectric Signals: Cross-Station Replication and Visitor-Driven Suppression in a Public Exhibition," Biomimetics, vol. 11, 2026.
[20] M. Maeder, "trees: Pinus sylvestris – Immersive Lab Version," Zurich University of the Arts (ZHdK), 2015. [Online]. Available: https://immersivelab.zhdk.ch/
[21] L. Zheng and Z. Guo, "Construction of Dynamic Lighting System Based on Chlorophyll Absorption Efficacy and Its Regulation Effect on Lettuce Growth," J. Photochem. Photobiol. B, Biol., vol. 256, 2026.
[22] N. Akter et al., "Impact of Light Spectral Combinations on Morphology, Yield, and Quality of Indoor-Grown Cilantro," Front. Plant Sci., 2025.
[23] S. Salisu Jibia et al., "Interactive Effects of LED Spectrum and Nitrogen Levels on Physiological Changes and Yield of Strawberry (Fragaria × ananassa Duch.)," Plants, vol. 13, no. 1, p. 89, 2024.
[24] P. V. Miller and C. Cox, "Music from Plant Biosignals: A Conceptual and Analytical Orientation," Music Theory Online, vol. 30, no. 1, 2024, doi: 10.30535/mto.30.1.6.

[25] A. Leudar, "Integrating Plant Electrophysiology, Plant Signalling and Art," Sonic Arts Research Centre, Queen's University Belfast, 2013.
[26] O. Brand, "The Photosynthesiser - A Methodology for Mapping Environmental Conditions, Pivotal to the Speed of Photosynthesis in Plants, Through Sonification," Ph.D. dissertation, University of Plymouth, 2020.
[27] "Symbiotic Biodata Sonification Board," HKU Bookstack. [Online]. Available: https://bookstack.hku.nl/books/bio-data-sonification-using-midi/
[28] A. Pulido Saravia, "AWECG-Monitor: Cardiac Monitor Using ESP32 and AD8232," GitHub repository, 2023. [Online]. Available: https://github.com/Alpusa/AWECG-Monitor
[29] S. Majumder, "AI-Based ECG Monitoring and Arrhythmia Detection Using ESP32, AD8232 & CNN," GitHub repository, 2025. [Online]. Available: https://github.com/SayantanM7/miniproject-ecg
[30] A. G. Volkov, Plant Electrophysiology: Methods and Cell Electrophysiology. Berlin, Germany: Springer, 2012.
[31] J. Fromm and S. Lautner, "Electrical Signals and Their Physiological Significance in Plants," Plant, Cell & Environment, vol. 30, no. 3, pp. 249–257, 2007.
[32] E. Davies, "New Functions for Electrical Signals in Plants," New Phytologist, vol. 161, no. 3, pp. 607–610, 2004.
[33] M. J. S. A. Amaral et al., "An Arduino-Based Low-Cost System for Plant Electrophysiology," J. Electr. Comput. Eng., vol. 2023, 2023.
[34] S. Mancuso and F. Baluška, Plant-Environment Interactions: From Sensory Plant Biology to Active Plant Behavior. Berlin, Germany: Springer, 2009.
[35] F. Baluška, S. Mancuso, and D. Volkmann, Communication in Plants: Neuronal Aspects of Plant Life. Berlin, Germany: Springer, 2006.