

Designing ESP32- and Phyphox-Based Experiments for Teaching Electric Current and Circuits in Grade 11 Physics

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ABSTRACT

Background: Practical work is central to physics education, but electric-current and circuit experiments in high schools often remain limited by equipment availability, manual data recording, and low visibility of real-time variation.

Objective: This study designed and evaluated a low-cost experimental system integrating an ESP32 microcontroller, a digital current/power sensor, and the Phyphox mobile application for teaching electric current and circuits in Grade 11 Physics.

Methods: The research combined literature review, technical design, experimental measurement, descriptive statistics, and expert evaluation. The device was designed to collect voltage and current data and display them as real-time numerical values and graphs on a smartphone. Two teaching applications were developed: volt-ampere characteristic/Ohm law verification and determination of electromotive force and internal resistance. Five high-school physics teachers evaluated the product using structured criteria.

Results: The designed system supported continuous data collection, real-time graphing, and classroom use for demonstration or group experiments. Teacher evaluation showed high scores for

technical characteristics (mean = 4.38/5), time and classroom organization (4.32/5), pedagogical value (4.54/5), and practical applicability (4.60/5). The overall mean was 4.44/5, with 98.9% of ratings at levels 4-5.

Conclusion: The ESP32-Phyphox experimental system is a feasible tool for improving visualization, data processing, and experimental competence in teaching electric current and circuits. Further classroom trials with larger samples are recommended.

Keywords: ESP32; Phyphox; digital power sensor; physics experiment; electric current; Ohm law; Grade 11 Physics.

INTRODUCTION

Laboratory work is widely regarded as a key component of science education because it helps learners connect observable phenomena with scientific ideas, develop experimental skills, and build evidence-based reasoning.^[20,21] In school physics, the topics of electric current and circuits require students to understand relationships among current, voltage, resistance, and electrical power. These relationships are often represented through numerical data and graphs, especially in experiments on Ohm law and closed circuits.

In practice, however, circuit experiments in high-school classrooms are frequently

constrained by limited equipment, aging meters, time-consuming setup, and manual data recording. These constraints may reduce opportunities for students to observe the variation of electrical quantities continuously and to process data within a normal lesson. In the context of competence-oriented education, such limitations create a need for compact, low-cost, and data-rich experimental systems that can be implemented in ordinary classrooms.

Smartphones and mobile applications have created new opportunities for physics experimentation. The Phyphox application enables data acquisition, display, analysis, export, and remote-control functions, and it has been used in a range of physics experiments.^[1-5] At the same time, microcontroller platforms such as Arduino and ESP32 can extend mobile experiments by connecting external sensors, collecting specialized data, and transmitting them wirelessly.^[6,10,11] ESP32 is particularly attractive for school experiments because it integrates Wi-Fi and Bluetooth capabilities and can communicate with smartphones or computer interfaces.^[12-15,24,25]

Despite these advantages, the integrated use of ESP32, a digital current/power sensor, and Phyphox for Grade 11 electric-current and circuit experiments has not been fully exploited. The present study addressed this gap by designing, building, and evaluating an experimental system that measured voltage and current, transmitted data to a mobile device, and supported real-time graphing for classroom teaching. The study aimed to (i) design and build the ESP32-based experimental system; (ii) establish a data acquisition and display procedure with Phyphox; (iii) evaluate stability and measurement suitability for educational purposes; and (iv) assess its applicability in teaching electric current and circuits in Grade 11 Physics.

LITERATURE REVIEW

The use of smartphones in physics education has been reported in mechanics,

waves, optics, magnetism, and other domains. Phyphox has been used to collect and visualize data from built-in smartphone sensors and to support collaborative classroom experiments.^[1-5] Research has also shown that smartphone-based experimentation can increase learners' interest and engagement when the activity is aligned with meaningful inquiry tasks.^[22,23] However, smartphone sensors alone do not always provide the specialized measurement range, calibration stability, or circuit integration required for electrical experiments.

Microcontroller-based measurement systems provide an alternative pathway. Arduino- and ESP32-based devices can be paired with external sensors and programmed for particular measurement tasks.^[6,10,11] The development of Bluetooth sensor support in Phyphox has further simplified the pathway from a microcontroller-based idea to a classroom experiment.^[6] ESP32 has also been used in open-source monitoring systems in energy and power-quality studies, demonstrating its usefulness for real-time data acquisition and communication.^[12-18]

For measurement of electrical quantities, integrated digital sensors such as the INA219 current/power monitor can provide current, voltage, and power data through an I2C interface.^[26] Such sensors make it possible to replace separate readings from voltmeters and ammeters with synchronized data streams. In a physics classroom, this feature can support real-time U-I graphs and help students connect the shape of a graph with the underlying physical law.

MATERIALS AND METHODS

Research design

The study used a design-based research orientation combining technical development and pedagogical evaluation. The work involved four stages: analysis of teaching content and classroom needs; design and construction of the experimental system; trial measurement and technical

verification; and teacher evaluation of classroom applicability.

The educational content was limited to the Grade 11 Physics topic of electric current and circuits, particularly voltage, current, resistance, electrical power, Ohm law, electromotive force, and internal resistance. The technical scope was limited to an ESP32 controller, a digital current/power sensor, supporting circuit components, and

the Phyphox mobile application for data display and analysis.

Participants and context

The practical context was investigated through teacher responses concerning the use of electric-current and circuit experiments. Five high-school physics teachers participated in the evaluation of the developed device. Their teaching experience is summarized in Table 1.

Table 1. Teaching experience of teachers participating in the evaluation

Criterion	Number	Percentage
Teachers with ≥ 15 years of experience	3/5	60%
Teachers with 10 to < 15 years of experience	1/5	20%
Teachers with 5 to < 10 years of experience	1/5	20%
Teachers with < 5 years of experience	0/5	0%

Technical design of the experimental system

The system consisted of an ESP32 microcontroller, a digital current/power sensor, electrical circuit components, a power source, and a smartphone running Phyphox. The sensor measured voltage and current in the experimental circuit; the ESP32 acquired and processed the sensor data and transmitted it wirelessly; Phyphox displayed numerical data and graphs in real time. The system was designed for low-voltage educational circuits and for use under teacher supervision.

Two classroom experiments were developed. The first experiment investigated the volt-ampere characteristic of a resistor and verified Ohm law by plotting voltage as a function of current. The second experiment investigated a closed circuit and determined the electromotive force and internal resistance of a source from the relationship between terminal voltage and current.

Evaluation procedure and statistical analysis

Teacher evaluation focused on technical characteristics, time and classroom organization, pedagogical value, and practical applicability. Items were rated on a

five-point scale, where higher values indicated stronger agreement or better suitability. Teachers also gave qualitative comments and recommendations for improvement.

The data were processed using descriptive statistics. Frequencies and percentages were used for contextual and multiple-choice responses. Mean scores and the percentage of ratings at levels 4-5 were calculated for evaluation criteria. No inferential statistical test was applied because the teacher sample was small and the study focused on product development and preliminary applicability rather than testing causal learning effects.

RESULT

Classroom need for a digital experimental system

The teacher survey indicated that the use of electric-current and circuit experiments was not frequent. The main difficulties are summarized in Table 2. The most prominent difficulties were the lack of equipment (80%), students' difficulty observing data variation (80%), old or insufficiently accurate equipment (60%), difficulty drawing graphs and processing data in class (60%), and difficulty organizing group experiments (60%).

Table 2. Difficulties commonly encountered in teaching electric-current and circuit experiments

Difficulty	Number of teachers	Percentage (%)
Lack of experimental equipment	4	80
Old or insufficiently accurate equipment	3	60
Time-consuming setup and measurement	1	20
Students had difficulty observing data variation	4	80
Difficulty drawing graphs and processing data in class	3	60
Difficulty organizing group experiments	3	60
Concern about electrical safety	0	0

Operation of the ESP32-Phyphox experimental system

The device measured voltage and current and sent the data to a smartphone interface. During operation, students could observe numerical values and the U-I graph as the circuit condition changed. This reduced manual reading and recording and allowed immediate discussion of the relationship between variables.

In the Ohm law experiment, the system supported the construction of a volt-ampere graph. The linear trend of the U-I relation could be observed directly, enabling

students to infer the resistance from the slope of the graph. In the internal-resistance experiment, changes in terminal voltage and current could be tracked to support analysis of source behavior in a closed circuit.

Teacher evaluation of the product

Teacher evaluation results were positive across all criteria (Table 3). The overall mean score of quantitative criteria was 4.44/5, and 98.9% of the ratings were at levels 4-5. The highest mean score was practical applicability (4.60/5), followed by pedagogical value (4.54/5).

Table 3. Teacher evaluation according to groups of criteria

Criteria group	Mean score	Ratings at levels 4-5 (%)	Brief interpretation
Technical characteristics	4.38	98.0	Compact device; multiple quantities measured; real-time display; accuracy suitable for teaching.
Time, operations, and classroom organization	4.32	98.0	Implementation time was appropriate; initial familiarization and connection preparation were needed.
Pedagogical value	4.54	100.0	The highest-rated group; clear advantages in visualization and experimental competence development.
Practical applicability	4.60	100.0	Potential for use in high schools if equipment, guidelines, and procedures are available.

Suitability of teaching applications

The proposed applications were considered suitable for classroom use, especially the volt-ampere characteristic and Ohm law verification activity (Table 4). Teachers

considered this application highly aligned with the central content of Grade 11 circuits because it provided immediate U-I data and graphs.

Table 4. Suitability of proposed teaching applications

Application	Mean score	Ratings at levels 4-5 (%)	Evaluation
Volt-ampere characteristic and Ohm law verification	4.60/5	100.0	Most suitable for the central content; U-I data and graph were displayed directly.
Closed circuit, electromotive force and internal resistance	4.16/5	88.0	Scientifically valuable but required more careful manipulation and data processing.
General use for demonstration, group work and STEM activity	4.32/5	96.0	Suitable as an integrated teaching device after preparation and guidance.

DISCUSSION

The findings suggest that the developed system responds directly to common difficulties in teaching circuit experiments. Traditional circuit experiments often require students to read several instruments, record separate values, and draw graphs after measurement. These steps can consume time and may shift attention away from interpreting physical relationships. By contrast, the ESP32-Phyphox system collected data continuously and displayed graphs immediately, allowing learners to focus more on recognizing patterns and explaining them.

The high teacher ratings for pedagogical value and practical applicability are consistent with previous studies showing that smartphone- and microcontroller-based experiments can increase the accessibility, flexibility, and interactivity of physics practical work.^[1,6,20,22,23] The system also extends ordinary smartphone experimentation because the measured quantities are acquired through an external digital sensor rather than relying only on built-in sensors. This is important for circuit topics, where voltage and current must be measured directly and synchronously.

Compared with traditional measurement arrangements, the proposed system offers clear advantages in data collection and representation (Table 5). Real-time visualization makes it easier for students to see how electrical quantities vary, and it creates opportunities for inquiry questions such as why the U-I graph is linear for an ohmic resistor or why terminal voltage changes when current changes in a real source. These opportunities are aligned with the view that practical work should help students link observations with scientific ideas.^[21]

Nevertheless, the system also has limitations. It depends on digital devices, wireless connection, and teacher familiarity with ESP32 and Phyphox. In addition, the evaluation sample was small and did not include controlled measurement of student learning outcomes. Therefore, the results should be interpreted as preliminary evidence of feasibility and pedagogical potential rather than conclusive evidence of learning effectiveness. Future research should include larger samples, classroom implementation with students, pre-test/post-test evidence, and more detailed calibration analysis.

Table 5. Comparison between traditional and ESP32-Phyphox experimental approaches

Criterion	Traditional approach	ESP32, digital sensor and Phyphox approach
Data collection	Read each value manually from voltmeters/ammeters or digital multimeters.	Continuous data collection with real-time display on a smartphone.
Graph representation	Students record tables and draw graphs manually; this is time-consuming and prone to error.	Graphs are displayed directly, helping students observe relations immediately.
Classroom interaction	Teacher demonstration often dominates; group work is harder to organize.	Supports demonstration, group experiments, and student-led data analysis.
Pedagogical emphasis	Focuses on measuring separate values and completing tables.	Emphasizes real-time visualization, interpretation, and experimental competence.

The improvement directions identified during evaluation are summarized in Table 6. These recommendations emphasize

preparation, guidance materials, backup plans, and broader empirical testing.

Table 6. Main limitations and suggested improvements

Limitation	Possible effect	Suggested improvement
Dependence on technology	Requires smartphone, Wi-Fi/ESP32 connection and Phyphox installation.	Prepare a teacher-controlled device and pre-install necessary files.
Need for	Teachers and students need time to learn	Provide concise user manuals and

familiarization	the new device.	demonstration videos.
Risk of connection interruption	Wireless connection may be unstable in some classrooms.	Test before class and prepare a backup traditional measurement plan.
Limited empirical sample	Teacher evaluation was based on a small group of five teachers.	Conduct broader classroom trials with student learning outcomes.

CONCLUSION

This study designed and evaluated an experimental system that integrated ESP32, a digital current/power sensor, and the Phyphox mobile application for teaching electric current and circuits in Grade 11 Physics. The system enabled real-time collection, transmission, display, and graphing of voltage and current data. It supported two teaching applications: volt-ampere characteristic/Ohm law verification and determination of electromotive force and internal resistance.

Teacher evaluation indicated positive perceptions of the device's technical characteristics, pedagogical value, and practical applicability. The results suggest that the system can help overcome limitations of traditional circuit experiments by reducing manual recording, improving visualization, and supporting data-based classroom discussion. However, the study remains preliminary because of the small evaluation sample and the absence of controlled student learning data. Further development should focus on user guidance, technical stability, calibration, safety instructions, and classroom trials with larger groups of teachers and students.

Declaration By Authors

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