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Development of Arduino-Based Light Energy Transmission Tool to Improve Students' Conceptual Understanding of Junior High School

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ABSTRACT

Light energy transmission is one of the topics in junior high school science (Physics) that potentially causes comprehension difficulties due to its abstract nature when delivered solely through theoretical instruction. A literature review of Arduino-based studies reveals two gaps: first, some studies focused only on measuring light intensity without examining light energy transmission through specific media; second, studies that measured transmission through transparent materials remained limited to ideal laboratory conditions and had not integrated assessments of students' conceptual understanding. This study aimed to develop a light energy transmission measuring teaching aid based on the Arduino ESP32 type, programmed using the Arduino IDE. The ESP32 was selected due to its advantages over conventional Arduino, integrated Wi-Fi and Bluetooth, enabling more accurate sensor readings and real-time data display. The novelty of this study lies in its focus on light energy transmission, utilization of ESP32, an LED flashlight as a contextual light source, testing on nako glass and no medium conditions, and direct assessment of students' conceptual understanding within a single integrated design. The method used in this study is the Research and Development (R&D) method with the ADDIE model design, conducted at SMP Negeri 7 Sigi involving 21 eighth-grade students of class VIII A. Data were analyzed using the N-Gain formula. The results showed an N-Gain score of 0.58 which falls in the moderate category, indicating an improvement in students' conceptual understanding after participating in the learning process by applying teaching aids in the learning.

INTRODUCTION

Natural Sciences (IPA) learning at the junior high school (SMP) level plays a strategic role in building students' scientific understanding of natural phenomena, where the national curriculum is designed to integrate conceptual and contextual approaches so that students not only understand concepts theoretically, but are also able to relate them to real experiences in everyday life (Andila et al., 2021; Hikmah et al., 2024; Rochma et al., 2023). Physics, as one of the branches of science, plays a central role as its study encompasses natural phenomena closely related to human life, thus effective physics learning must be able to foster deep and meaningful understanding so that students are capable of applying their knowledge in solving real-world problems (Subella et al., 2023; Haq & Raicudu, 2023; Sari et al., 2023; Sa'adah et al., 2025). One of the fundamental concepts in physics that has high relevance to everyday life is light energy transmission, which explains how light interacts with various types of matter through three main mechanisms, namely absorption, reflection, and transmission (Sheftyawan et al., 2018; Rahmawati et al., 2021), and whose phenomena can be directly encountered in students' daily lives, such as in the use of window glass, mirrors, and various types of transparent and opaque materials in their surroundings.

Based on the results of preliminary observations conducted at SMP Negeri 7 Sigi, it was found that students' understanding of the concept of light energy transmission was still relatively low. Students experienced difficulties in explaining the differences between materials that transmit light and those that do not, interpreting transmission phenomena in real-life contexts, and solving problems related to the concept. This condition was caused by a learning process still dominated by lecture-based theoretical approaches, without the support of interactive learning media or teaching aids that would allow students to make direct observations of the phenomena being studied. As a result, student engagement and motivation in learning tended to be low, and opportunities to obtain meaningful learning experiences became very limited (Ibrahim et al., 2018; Syukron & Elviyanti, 2021; Wicaksiwi et al., 2023).

Interactive learning supported by appropriate media has been proven to enhance students' conceptual understanding as well as their critical and analytical thinking skills (Pangke et al., 2021; Wulandari et al., 2024). Furthermore, the use of teaching aids in physics learning can help concretize abstract concepts and improve student motivation and learning outcomes (Sari & Nugroho, 2021; Af'idah et al., 2023). In a broader context, the use of Arduino-based microcontrollers in physics and science education has been proven to significantly improve students' conceptual understanding and learning motivation, and its relevance is not limited to engineering and electronics learning alone, but is also effective as an experimental medium in core physics topics such as optics, thermodynamics, and energy at the secondary school level (Banda & Nzabahimana, 2021; Erol & Demir, 2024; Novriensi et al., 2024; Oh, 2025). Along with technological advancements, microcontroller-based tools such as Arduino provide opportunities to create more effective experimental learning environments, particularly with the use of ESP32 which supports real-time data processing and connectivity (Wagyana & Rahmat, 2019; Anselmo et al., 2024; Wahyudi et al., 2024). Furthermore, previous studies have shown that Arduino-based tools can improve students' psychomotor skills in learning activities (Saputri et al., 2017).

Nevertheless, a review of previous studies reveals several unanswered gaps. Verawati et al., (2022) developed an Arduino Uno-based teaching aid that integrated a Solar Cell, ultrasonic sensor, and Light Dependent Resistor (LDR) for energy topics in science learning. Although the study successfully improved students' skills, the developed tool was only capable of measuring light intensity at a single point statically, without examining how much light energy was actually transmitted when passing through a specific medium. Furthermore, Erol & Demir (2024) developed an experimental procedure for measuring light transmission through transparent materials using Arduino Uno and an LDR sensor in the context of STEM education. Although that study had addressed the aspect of light transmittance, its measurements were limited to the thickness of acetate material under controlled laboratory conditions, and had not examined its direct impact on students' conceptual understanding in the classroom. Consequently, there exists a significant research gap, namely the unavailability of a microcontroller-based learning tool specifically designed to measure light energy transmittance using contextual media relevant to students' daily lives, while simultaneously providing empirical evidence of improvements in students' conceptual understanding in physics science learning in the classroom.

To address these gaps, this study developed an Arduino-based learning teaching aid using the ESP32 38 GPIO type, programmed through the Arduino IDE. The ESP32 was selected as a solution to the limitations of conventional microcontrollers due to its advantages, including a dual-core 240 MHz processor, integrated Wi-Fi and Bluetooth, and 18 ADC channels that enable more accurate sensor readings and real-time data display. The novelty of this study encompasses four aspects, namely: first, the use of ESP32 with higher capacity and connectivity compared to conventional Arduino used in previous studies; second, the utilization of an LED flashlight as a light source that is more practical and easier to operate in classroom learning conditions; third, the testing of light energy transmission under two comparative conditions, namely without a medium and using a nako riben glass medium that is relevant to students' daily lives, allowing students to directly connect experimental data obtained with the theoretical concepts being studied; and fourth, the direct measurement of the impact of teaching aid use on improving students' conceptual understanding in physics science learning in the classroom, which has not been conducted in previous studies. This approach is in line with the principles of experiential learning recommended in science education (Efraim et al., 2025; Acheampong et al., 2024).

Based on the foregoing, this study aims to develop an Arduino ESP32-based light energy transmission measuring teaching aid to improve students' conceptual understanding in physics science learning at SMP Negeri 7 Sigi.

METHOD

This study employed a Research and Development (R&D) design using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) to develop an Arduino-based teaching aid for measuring light energy transmission. The Analysis phase was conducted to identify learning needs and existing problems in the field through preliminary observation. The Design phase was carried out to plan and construct the Arduino-based teaching aid along with the required research instruments. The Development phase was conducted to trial the teaching aid that had been constructed and to validate it with expert reviewers in order to assess the feasibility of the tool prior to implementation. The Implementation phase was carried out by applying the teaching aid that had been declared feasible to students during the learning process. The Evaluation phase was conducted to assess the success and feasibility of the developed teaching aid based on the collected data. The research diagram can be seen in Figure 1.

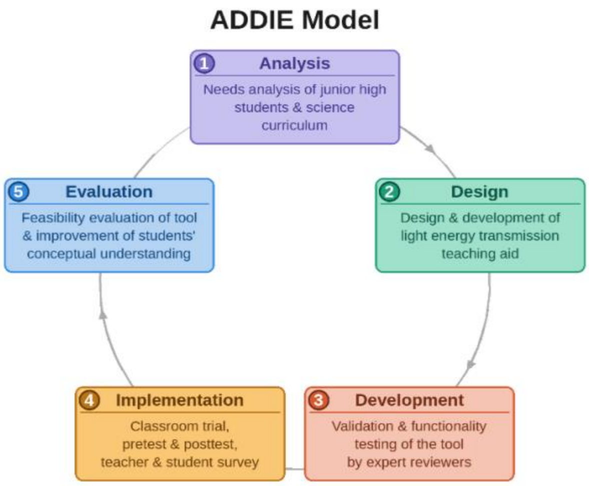

Fig.1. ADDIE model

The study was conducted at SMP Negeri 7 Sigi during the 2025/2026 academic year over two meetings, involving 21 students from class VIII A who were selected through purposive sampling, with participants generally aged 13–14 years.

The data collection techniques used in this study included observation, documentation, and questionnaires. Observation was conducted at the initial stage of the research to identify learning conditions and problems directly. Documentation was used to collect supporting data in the form of documents relevant to the study. Questionnaires were used to collect data on teachers' and students' responses toward the developed teaching aid using a Likert scale of 1–4.

The research instruments consisted of expert validation sheets, teacher and student response questionnaires, as well as a pretest and posttest comprising 15 multiple-choice questions. The pretest and posttest were used as supporting data to observe the improvement of students' conceptual understanding before and after using the developed teaching aid within a single class without a control class. The selection of a single class in this study was based on the research focus, which was oriented toward the development of a teaching aid rather than the comparison between groups. The primary objective of this study was to assess the feasibility and quality of the developed teaching aid in improving students' conceptual understanding; therefore, the use of a control class was not required, as this study did not aim to examine differences in effectiveness between two groups, but rather to observe the improvement of students' conceptual understanding before and after using the teaching aid within the same class.

All data were analyzed using quantitative and qualitative approaches. Expert validation results were analyzed using a feasibility percentage formula. Teacher and student response questionnaire data were analyzed using mean scores. The improvement of students' conceptual understanding was measured using N-Gain based on a comparison of pretest and posttest scores within the same single class without involving a control class, with categories of high ($g > 0.7$), moderate ($0.3 \leq g \leq 0.7$), and low ($g < 0.3$) (Hake, 1999). Qualitative data from validator feedback were analyzed descriptively, and all data analysis was conducted using Microsoft Excel.

RESULTS AND DISCUSSION

Analysis Stage

At the analysis stage, an initial study of the learning process at SMP Negeri 7 Sigi was conducted. The results showed that the learning process was still dominated by theoretical explanations and had not optimally utilized learning media that could provide direct and concrete examples to students. This condition resulted in low levels of students' understanding, interest, and engagement in the learning process.

To address this problem, the researcher developed an Arduino-based teaching aid to measure light energy transmission using an ESP32 microcontroller. This tool is capable of displaying measurement results in real time through Google Spreadsheet, allowing students to observe experimental data directly. The use of this tool is expected to bridge the gap between theoretical concepts and real observations. However, the effectiveness of a teaching aid is not only determined by its technical performance but also by its impact on the learning process. Therefore, teacher and student response questionnaires as well as pretest and posttest were conducted to evaluate the effectiveness of the developed tool in improving students' conceptual understanding.

Design Stage

At the design stage, the product developed was an Arduino-based teaching aid using the ESP32 type to measure light energy transmission, with the design process involving several steps beginning from designing the design or model of the tool to be developed, the preparation of the required tools and materials, to the design of the teaching aid in which the researcher assembled the receiver circuit by connecting the ESP32, LDR sensor, and a 10 kΩ resistor, where the first leg of the LDR was connected to the 3V3 pin of the ESP32 as the voltage source, the second leg of the LDR was connected to the first leg of the 10 kΩ resistor, the junction point between the two was connected to the GPIO34 pin as the voltage signal input representing light intensity, and the remaining leg of the resistor was connected to the common GND to complete the voltage divider circuit, while directly beside the LDR sensor, a solar panel was placed side by side within the same teaching aid enclosure so that both could receive light exposure from the same source simultaneously, however the measurement of current and voltage on the solar panel was carried out manually using a multimeter and was completely separate from the electronic system integrated with the ESP32, then after the entire circuit was assembled the system was programmed and integrated with Google Spreadsheet for automatic recording of light intensity data, and the design stage concluded with the construction of a testing box aimed at minimizing interference from external light sources so that the measurement results obtained were more accurate and controlled. The design of the teaching aid developed can be seen in Figure 2.

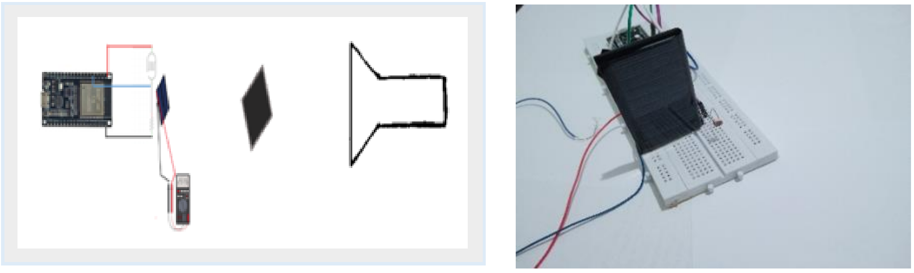

Fig.2. Design of the Arduino-based light energy transmission measurement tool

Development Stage

Product development

At the development stage, the ESP32-based learning tool that had been constructed during the design stage was subsequently refined prior to validation. The refinement process included functional testing of all components, repair of circuit connections, and program adjustments in the Arduino IDE to ensure that the ESP32 could accurately read and display light intensity data in real-time. The enclosed testing box was also refined to minimize interference from external light sources. In addition to the light intensity sensor, the tool was also equipped with a solar panel as an additional observation object, where the current and voltage generated by the solar panel were measured manually using a multimeter so that students could directly observe and understand the principle of converting light energy into electrical energy through real measurements. The solar panel circuit was deliberately designed separately from the main ESP32 circuit based on careful technical and pedagogical considerations. Technically, the solar panel produces varying voltage and current depending on the light intensity it receives, so if directly connected to the ESP32 system without proper regulation, there is a risk of damage to the microcontroller components. Pedagogically, the separation of the circuits allows students to study two concepts independently and simultaneously, namely the measurement of light intensity through a digital sensor and the measurement of the electrical energy output of the solar panel through an analog measuring instrument, so that conceptual understanding becomes more comprehensive and contextual. Once all components functioned properly and were integrated with Google Spreadsheet, the teaching aid was submitted to media and content experts for feasibility validation before being implemented in the learning process.

Media validation

The media validation was carried out by experts from the Physics Education Program at Universitas Tadulako to evaluate the feasibility of the developed product. The assessment covered aspects of tool quality, media suitability, and device performance, using a Likert scale from 1 to 4, where 1 indicates "Very Infeasible" and 4 indicates "Very Feasible", as presented in Table 1.

Table 1. Media Validation Results

	Aspect	Score	Category
	Tool Quality	3.67	Very Feasible
	Media Suitability	4.00	Very Feasible
	Tool Performance	4.00	Very Feasible
Average		3.89	Very Feasible
Validation Percentage		97%	Very Feasible

The results of media expert validation of the teaching aid indicated that all assessment aspects received a very feasible category. The tool quality aspect obtained a score of 3.67, the media suitability aspect obtained the highest score of 4.00, and the tool performance aspect also obtained a score of 4.00, with an overall average of 3.89 and validation percentage 97% in the very feasible category, which demonstrates that the ESP32 and LDR sensor-based teaching aid developed has met the learning media feasibility standards in terms of quality, suitability, and performance.

Device power calculation

At the development stage, not only was the device implementation carried out, but also an analysis of the performance of the main components, particularly in the transmitter and receiver sections. Transmitter and receiver calculations were performed to determine and ensure that the developed teaching aid was capable of operating in accordance with the expected specifications. Based on the calculations that have been carried out, the data obtained are presented in Table 2.

Table 2. Transmitter Results

Power (Watt)	Voltage (volt)	Electric Current (Ampere)
50	3.7	13,5

The light source used in the testing of the teaching aid was an LED flashlight with a power of 50 watts, a voltage of 3.7 volts, and an electric current of 13.5 amperes. The LED flashlight was selected because it produces more directed, stable, and efficient light compared to conventional light sources, making it suitable for use as a light source in consistently measuring light energy transmission in the classroom.

In the receiver power testing, two conditions were used as a comparison, namely without nako glass and using nako glass. The calculation data without nako glass can be seen in Table 3.

Table 3. Receiver Results Without Nako Glass

Distance	Device Intensity	Aplikation Intensity	*Receiver* Power ($\times 10^{-5}$ w)	Efficiency
1 m	68,82	700	35,1	0,000702%
2 m	62,68	173	10,85	0,000217%
3 m	56,55	52	5,3	0,000106%
4 m	50,41	24	0,97	0,0000194%
5 m	48,46	20	0,66	0,0000132%

Table 3 shows that the greater the distance between the light source and the receiver sensor, the more the detected light intensity decreases. This is evidenced by the intensity value decreasing from 68.82 at a distance of 1 meter to 48.46 at a distance of 5 meters, accompanied by a significant reduction in receiver power and efficiency. This phenomenon indicates that propagating light undergoes energy attenuation as the distance increases, because light energy spreads in all directions during its propagation, resulting in less energy being successfully transmitted and received by the sensor. This pattern directly represents the nature of light energy transmission in the topic of light and its properties in junior high school science learning, whereby the ability of light to transmit its energy is inversely proportional to the distance traveled. Furthermore, the calculation data using nako glass can be seen in Table 4.

Table 4. Receiver Results Using Nako Glass

Distance	Device Intensity	Aplikation Intensity	*Receiver* Power ($\times 10^{-5}$ w)	Efficiency
1 m	62,92	213	18,9	0,000378%
2 m	57,43	50	1,31	0,0000262%
3 m	51,95	28	0,52	0,0000104%
4 m	46,46	8	0,18	0,0000036%

Distance	Device Intensity	Aplikation Intensity	*Receiver* Power ($\times 10^{-5}$ w)	Efficiency
5 m	42,87	5	0,07	0,0000014%

Table 4 presents the results of light energy transmission measurements when passing through a nako glass medium at various distances. Compared to measurements without a medium, the intensity and receiver power values in this table are overall lower, which demonstrates that nako glass absorbs and reflects a portion of light energy so that not all light is successfully transmitted. At a distance of 1 meter, most of the light could still be transmitted with an intensity of 62.92 and a receiver power of 18.9×10^{-5} A·W, however, as the distance increased to 5 meters, the intensity dropped to 42.87 and the receiver power decreased to only 0.07×10^{-5} A·W with an efficiency of 0.0000014%, meaning that most of the light had been blocked by the medium. This phenomenon directly illustrates the nature of light transmission through a semi-transparent medium, namely that not all light energy can be fully transmitted because a portion is absorbed and reflected by the medium through which it passes, resulting in progressively less energy reaching the receiver due to the combined effect of distance and the characteristics of the medium.

Implementation Stage

The implementation stage was carried out in class VIII A at SMP Negeri 7 Sigi over two meeting sessions, actively involving both teachers and students in operating the developed teaching aid for measuring light energy transmission. The direct involvement of students in operating the device was intended to allow them to empirically observe and understand how light undergoes changes in intensity when passing through a specific medium, such as ribbed glass, which constitutes the core of the light energy transmission concept. Through direct observation of data displayed by the LDR sensor and the measurement results of the mini solar panel using a multimeter, students were able to construct the conceptual understanding that the intensity of transmitted light is influenced by the optical properties of the medium through which it passes, while simultaneously witnessing how light energy is converted into measurable electrical energy. To evaluate the response to the developed device, teachers and students completed questionnaires consisting of 13 statement items for teachers and 10 statement items for students, aimed at assessing the feasibility, ease of use, and usefulness of the tool in the learning process. Furthermore, to determine whether the developed tool was genuinely capable of improving conceptual understanding, students were administered a pre-test and post-test consisting of 15 multiple-choice questions. The implementation process in the classroom can be seen in Figure 3.

Fig.3. Documentation of the implementation phase showing the learning process using the Arduino-based teaching aid and students completing the response questionnaire

Teacher response

The teacher's response to the developed teaching aid was assessed based on three aspects, namely tool quality, media suitability, and tool performance. The results of the teacher's response assessment can be seen in Table 5.

Table 5. Teacher Response Results

Aspect	Score	Category
Tool Quality	3.66	Very Good
Media Suitability	3.82	Very Good
Tool Performance	3.83	Very Good
Average	3.77	Very Good

Based on the table above, the developed teaching aid received a very positive response from teachers. Based on questionnaire response data from two science teachers regarding the developed teaching aid, an average score of 3.77 was obtained, which falls into the "very good" category. These results indicate that the teachers considered the developed teaching aid feasible for use in the learning process, both in terms of physical quality, its suitability with the junior high school science curriculum, and its ability to display data accurately during practical activities.

Student response

The student's response to the developed teaching aid was assessed based on three aspects, namely tool quality, media suitability, and tool performance. The results of the student's response assessment can be seen in Table 6.

Table 6. Student Response Results

Aspect	Score	Category
Tool Quality	3.59	Strongly agree
Media Suitability	3.60	Strongly agree
Tool Performance	3.65	Strongly agree
Average	3.61	Strongly agree

The field results showed (Table 6) that students responded positively to the use of the Arduino-based light energy transmission measuring teaching aid as a learning tool, with an average score of 3.61, which falls into the "strongly agree" category. Furthermore, during the learning process, students demonstrated high enthusiasm when the teaching aid was introduced, as evidenced by their active participation in asking questions and engaging in discussions related to the use and working principles of the developed teaching aid.

Learning outcomes

As supporting data, a pretest-posttest was conducted to determine the improvement of students' conceptual understanding before and after using the developed teaching aid. The pretest-posttest results can be seen in Table 7.

Table 7. Pretest-Posttest Results

Aspect	Value
Students	21
Pretest	53,76
Posttest	80,05
N-Gain	0,58
N-Gain (%)	59%
Categori	Moderate

The Table 7 presents supporting data indicating that the developed learning tool was able to improve conceptual understanding in 21 students. The average pre-test score of 53.76 reflects the students' initial level of understanding before using the developed tool, while the post-test score of 80.05 indicates an increase in conceptual understanding after students used it. This improvement was then calculated using Hake's (1999) N-Gain formula, which is the difference between the post-test and pre-test scores divided by the difference between the ideal maximum score and the pre-test, resulting in an N-Gain value of 0.58, equivalent to 59%. Although the improvement is categorized as moderate based on Hake's criteria, this result still proves that the developed tool contributes significantly to helping students understand the concepts being learned. Therefore, it can be said that the development of this tool has provided significant benefits although there is still room for further improvement. Because this result is clear evidence that through this tool, students can build a new understanding that electrical energy can be transmitted without cables, a concept that was previously poorly understood by students and has now been successfully internalized through direct experience using the developed tool.

Evaluation Stage

The evaluation stage was carried out as a continuation of the development and implementation process, with the aim of identifying limitations and determining the improvements needed to optimize the developed teaching aid. Based on the overall findings, the Arduino-based teaching aid was able to function well and provide meaningful learning experiences for students. When junior high school students interacted directly with this tool, their understanding became more concrete because abstract concepts that were previously only understood through memorization could now be observed through real-time data. Students not only saw the measurement results, but also understood the process of how light can carry and transmit energy without a cable medium, thereby encouraging curiosity, critical thinking, and awareness that future technological developments may very well lead to more flexible energy transmission systems that are not entirely dependent on conventional cables, an achievement that is difficult to obtain through conventional text-based or lecture-only learning approaches.

From the perspective of measurement performance, the evaluation was carried out by comparing the light intensity results from the teaching aid with the Lux Light Meter application as a reference. Both instruments showed a consistent pattern, namely that light intensity decreased as the distance from the light source increased. When students directly observed this pattern of intensity decrease, they were able to build their own understanding that light as a form of energy weakens with distance, a concept that they previously only knew through memorization. Furthermore, the use of nako glass as a medium produced a more significant reduction in light intensity, so that students could also directly witness how the properties of a medium affect light energy transmission. The small difference between the device values and the reference application was considered reasonable and actually became productive discussion material in the classroom regarding the concept of measurement tolerance and the influence of environmental conditions. This is in line with Erol & Demir (2024) who affirmed that Arduino-based light transmission measurement experiments through transparent materials are able to create a dynamic learning environment and encompass achievements in the fields of science, technology, engineering, and mathematics simultaneously. Meanwhile, compared to Verawati et al. (2022) who developed an Arduino-based energy material teaching aid and concluded that the tool could help teachers provide understanding of energy material to students, this research goes further by integrating real-time data display and the ability to observe the effect of a medium on light transmission, so that students do not merely receive information but are directly involved in the process of measuring and interpreting data independently.

Overall, the implementation of this teaching aid with students demonstrated that the device was not only technically functional, but also pedagogically meaningful in transforming students' conceptual understanding from abstract to more concrete and contextual forms. When junior high school students were introduced to and directly interacted with the developed teaching aid, their understanding became more tangible because previously abstract concepts could now be observed directly. Students not only observed the measurement results, but also understood the process by which light can carry energy. This helped enhance curiosity, critical thinking, and awareness that future technological developments are likely to lead toward more flexible, efficient energy transmission systems that are not entirely dependent on cables. This is consistent with the principle that the use of teaching aids provides concrete and visual learning experiences, helping students understand concepts more effectively while also increasing their active engagement in the learning process. It should be understood that this study intentionally employed a one-group pretest–posttest design without a control group, since the primary objective of the research was to develop and evaluate the feasibility of the teaching aid, rather than to establish a causal relationship between the use of the tool and learning outcomes through a purely experimental approach. In the context of development research, the pretest and posttest data were not intended to serve as instruments for measuring learning effectiveness in a causal sense; instead, they functioned as supporting data to provide an initial indication that the developed tool has genuine potential to assist students in understanding the concept of light energy transmission. More specifically, the pretest was used to capture students' initial level of understanding before interacting with the tool, while the posttest was used to identify whether there were changes in understanding after students used it directly not to claim that such changes were solely caused by the developed teaching aid.

CONCLUSION AND SUGGESTION

Based on the research results, it can be concluded that the Arduino-based teaching aid developed is valid, feasible to use, and capable of improving students' conceptual understanding of light energy transmission, although the improvement falls within the moderate category. The integration of the LDR sensor and Google Spreadsheet helps students understand the concept more concretely through real-time data observation, while the inclusion of a solar panel with manual current and voltage measurements using a multimeter further enriches students' understanding of light energy conversion. The moderate improvement indicates that the teaching aid has positively contributed to bridging abstract concepts with concrete learning experiences, though further optimization is still needed. Suggestions for further research are to develop similar teaching aids for other science materials and to implement them over a longer period of time to optimize students' conceptual understanding more thoroughly.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest, whether financial, professional, or personal among all authors, that could affect the objectivity of the research conducted, nor the process of writing and publication of this article.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization of this research was carried out by H.L. and K.A.A.U.; product development was conducted by K.A.A.U. and U.W.; research methodology design was performed by the H.L.; writing and preparation of the original manuscript draft was carried out by R.S. and H.L.; and review and editing of the manuscript was conducted by all authors. All authors have read, reviewed, and approved the final version of the manuscript.

DECLARATION OF GENERATIVE AI SOURCES

During the preparation of this manuscript, the authors used Claude (Anthropic) and DeepL for language enhancement, grammar checking, translation, and structural refinement. All generated content was carefully reviewed, revised, and verified by the authors, who take full responsibility for the final content of the manuscript.

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