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Simulating the Inverse Square Law Using Light and Its Applications in Radiotherapy Physics

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Abstract

Inverse Square Law (ISL) is the basic principle of radiotherapy to achieve patient safety and effective delivery of doses. But the practical education of students on this law through practical ionizing radiation is very risky and very costly. In this project, we came up with a safe educational alternative, which is an optical analogy. The circuit is made up of a high intensity LED that is the source, four Light-Dependent Resistors (LDRs) that are the detectors and which are controlled by an Arduino Nano microcontroller. A laser sensor of VL53L1X was incorporated to make sure the distance is accurately measured. Several different distances were sampled in order to study the correlation between light intensity and distance and a graph of light intensity (I) against 1/r 2 was drawn. The data were quite close to the theoretical curve; e.g. the moving of the distance between 19.0 cm to 21.8 cm, which led to the decrease of the light intensity to about 30-70 percent. The device is therefore a low-cost educational instrument which enables medical physics students to experimentally confirm the inverse square law without being subjected to ionizing radiations.

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1. Introduction

The Inverse Square Law (ISL) is not just a school book formula, but a very important parameter in contemporary radiotherapy. Recent clinical research points out that patient positioning is important to the success of the treatment. To make a case in point, the studies of modern methods, such as VMAT and IMRT, reveal that the setup errors or even minor changes in patient position significantly affect the dose of the radiation to the tumor and healthy organs [1, 2]. Even slight changes in distance, as little as 3 mm, may cause high variation in the planned dose and the delivered dose [3]. This great distance sensitivity substantiates the fact that all medical physicists have to contend with deep practical comprehension of the Inverse Square Law in order to achieve the safety and the effectiveness of patient treatment [4].

Effective practical training of medical physics is challenged by a serious difficulty although it is incredibly important. According to recent educational survey studies, it is reported that it is quite expensive and costly to set up traditional hands-on laboratories where real medical equipment is used and very financially impractical in many institutions [5]. Moreover, clinical settings such as the X-ray rooms or Nuclear Medicine departments are often closed because of safety measures and high operation complexities and therefore, the students are not able to engage with the real-world devices [6]. In turn, these obstacles prompt educators to address the immediate necessity of the so-called innovative teaching techniques and contemporary pedagogical technologies to update the curriculum and get past these barriers [7].

To overcome such constraints, the present research is based with a contemporary technological idea with microcontrollers. Recent research is firmly in favor of the integration of Arduino into undergraduate physics laboratories, and there exists a strong emphasis on the ability of the system to impart so-called "21st-century skills" and STEM education [8]. It has been verified in literature that Arduino-based systems are used as low-cost embedded systems that are effective in data acquisition [9].

Moreover, those hands-on experiments motivate students to participate in physical phenomena first-hand, which gives them an insight in a compared way than simple theoretical work [10]. We can take advantage of this technology and offer a safe optical simulation system which mimics the effects of radiation but with no associated dangers**.**

Here we propose a specific educational simulation model and develop it to come up with the gap between theory and practice. The system employs the use of high-intensity LED as a representation of the radiation source and Light-Dependent Resistors (LDRs) as detectors, which are regulated by an Arduino Nano microcontroller. Most importantly, there is a VL53L1X laser time of flight sensor to make sure that distance measurements are highly accurate. The arrangement is designed in a very specific way to illustrate the Inverse Square Law (ISL) in the framework of radiotherapy physics and enables students to see and confirm the geometric fall-off of intensity in a safe and cost-effective way.

2. Literature Review

The inverse square law (ISL) is one of the key geometric concepts in external beam radiotherapy as it is directly related to how distance alterations lead to quantifiable dose alterations. This relationship can be of critical importance in clinical practice during such advanced procedures as Volumetric Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiation Therapy (IMRT) when extremely conformal dose distributions have to be applied in a tight proximity to at-risk organs. Sun et al. investigated the effect of setup errors on the stability of linac-based VMAT plans and demonstrated that comparatively minor variations in patient positioning can cause significant relative changes in target coverage and dose uniformity [1]. Their effort proves that distance is not a parameter involving abstract planning, but a sensitive variable that can undermine plan weight in case it is not managed.

Similar conclusions were also made by Havnen-Smith, in the breast radiation therapy where it was demonstrated that setup tolerance had a distinct dosimetric effect on the planning target volume as well as neighbouring normal tissues [2]. The slight variations in the position of patients and source-to-surface distance (SSD) in that research produced clinically significant variations in the amount of delivered dose, and the authors emphasize the practicality of the inverse square law in standard treatments [2]. Combined, these researches [1, 2] point towards the fact that the uncertainty at the millimetre level distance may compound to create non-trivial dose variations, particularly in methods that are sensitive to steep dose gradients and narrow margins.

From an educational perspective, these findings imply that medical physics students must develop more than a purely mathematical familiarity with the ISL. They need to understand how a simple $1/r^2$ relation underpins the behaviour of real treatment beams, why setup accuracy is so strictly controlled in clinical protocols, and how minor geometric errors can propagate into underdosage of the tumour or overdosage of healthy tissue [1, 2]. However, demonstrating these effects directly on clinical linacs is often constrained by safety considerations, limited machine time and the need to prioritise patient treatments.

This creates a clear pedagogical need for dedicated teaching tools that can illustrate distance–dose relationships in a safe, controlled and accessible way, while remaining conceptually faithful to the physics observed in VMAT and breast radiotherapy practice [1, 2]. The proposed simulation device of this work is structured in such a way that it will react to this requirement by converting the same ISL behaviour into a low-risk optical experiment that can be repeated and investigated by students without utilisation of ionising radiation.

3. Theoretical Background

3.1. Introduction

One of the fundamental physical laws is the Inverse Square Law that describes the propagation of energy in space. According to it, the strength(I) of radiation falling out of a point radiator is directly proportional to the inverse of the square of the distance between a radiator (r) [1]. This implies that doubling of distance will reduce the intensity to a quarter of the initial one.

Mathematically, this relationship is expressed as:

$$I \propto \frac{1}{r^2}$$

Or, to compare two different distances:

$$I_1 \cdot r_1^2 = I_2 \cdot r_2^2$$

This occurs due to the spread of radiation which is in a spherical manner. The further the distance the higher is the surface area of the same amount of energy ($A = 4\text{pi}\ r^2$) and the more the intensity is rapidly decreasing [2].

3.2. Importance in Medical Physics

This law is not merely a theory as in the case of radiotherapy, it is an essential consideration of safety. It governs two main aspects:

1. **Dose Accuracy:** In designing treatment of cancer, the medical physicists have to calculate the dose that will reach the tumor. Any slight error in the distance (Source-to-Surface Distance) causes a huge error in the dose delivered, which might impact on a successful treatment [3].

2. **Radiation Protection:** Safe distances of medical staff are determined through the use of the law. The exponent of distance is four and doubling the distance with a radioactive source would decrease the previously mentioned exposure by a factor of four and distance is a strong line of defense [5].

3.3. The Optical Analogy

It is dangerous and costly to teach these concepts by real ionizing radiation (such as X-rays). But, as both visible radiation and gamma rays are electromagnetic waves, they obey exactly the same Inverse Square Law geometry [2]. Hence, this project employs a high intensity LED to model the radiation source and Light Dependent Resistors (LDRs) to model the radiation detector. This is both a safe and a hands-on way of verifying the law with no health hazards.

3.4. System Components

In order to simulate this electronically we consider**:**

- **Arduino Nano:** The central processing unit [7].
- **LDR Sensor:** Adapts its own resistance to that of a Geiger counter depending on the intensity of the light**.**
- **Laser Sensor (VL53L1X):** It is a tool that is employed to determine the distance with a one-millimeter accuracy in order to make the findings valid.

4. Project Objectives

The main aim of this study is to develop and construct a working simulator. The specific objectives are:

- **Primary Objective:** To provide experimental evidence of the dependence of light intensity and distance that gives physical evidence of the Inverse Square Law.
- **Educational Objective :** To design an educational aid to medical physics students to visualize and appreciate the importance of distance that is of the utmost importance in the planning of radiation dose.
- **Practical Objective:** To fill the current knowledge gap between the abstract theory and the hazardous clinical practice through the provision of the low cost hands-on and risk-free simulation system.

5. Methodology

5.1. Research Problem

As already noted, the issue of inconsistency between the conceptual significance of the ISL and the challenge of proving it in practice is the primary challenge. Conventional practice on real radiotherapy equipment can be financially unsustainable and limited with a high level of safety measures [5, 6]. Therefore, medical physics students should have a secure experimental backup, to learn why a slight alteration of distance is a significant clinical incident and do not risk themselves, to dangerous ionizing radiation. Thus, we suggest an optical simulation system to fill this education gap.

5.2 Proposed Solution

In order to meet this, we enacted the Analogous Physical Simulation methodology. The rationale behind this is that visible light and the gamma rays are physically identical as they are both electromagnetic waves and follow the same Inverse Square Law geometry. The behavior of radiation is mimicked by our system where we use a high-intensity LED as the source and LDR sensors as the detector [2]. The Arduino Nano platform was our choice of what the literature has called the brain of the project because Arduino-based systems were confirmed to be cheap and extremely efficient pedagogical tools to illustrate the physics concepts [7]. Section 5 gives the detailed hardware design and software running of this system.

6. Design and Implementation

The chapter is an account of the hardware, the architecture of the system and the software logic that was used in testing the Inverse Square Law. It is a microcontroller-based design that aims at ensuring that the system is compact, precise, and automated.

6.1. Components Used

The system is subdivided into two major parts namely the Receiver Unit (Detector) and the Transmitter Unit (Source).

A. Receiver Unit (Simulating the patient/detector):

- **Arduino Nano:** Serves as the central microcontroller to process data.
- **Four LDR Sensors:** Arranged in a specific array to obtain a stable average light intensity reading, minimizing experimental errors.
- **OLED Screen (0.96", I2C):** A small display used to show the distance and intensity results instantly.
- **Potentiometer (10kΩ):** A variable resistor used to calibrate the system and adjust the threshold for ambient background light.
- **Buzzer:** Provides an audio feedback "beep" to confirm when a valid reading is successfully recorded.

B. Transmitter Unit (Simulating the radiation source):

- **High-Intensity LED:** Acts as the point source of radiation (light).
- **Laser Distance Sensor (VL53L1X):** Used to measure the exact distance between the source and the detector with millimeter precision.
- **Push Button:** Used to trigger the measurement process manually.
- **220Ω Resistor:** Connects in series with the LED to limit the current and protect the component.

6.2. System Architecture and Wiring

As an example of the general structure of the proposed system, a Block Diagram has been provided in Figure 1. This is a diagram that illustrates how data flows to the sensors (VL53L1X, LDR array and Control Button) to the processing unit (Arduino Nano) and then to the output units (OLED Display and Buzzer).

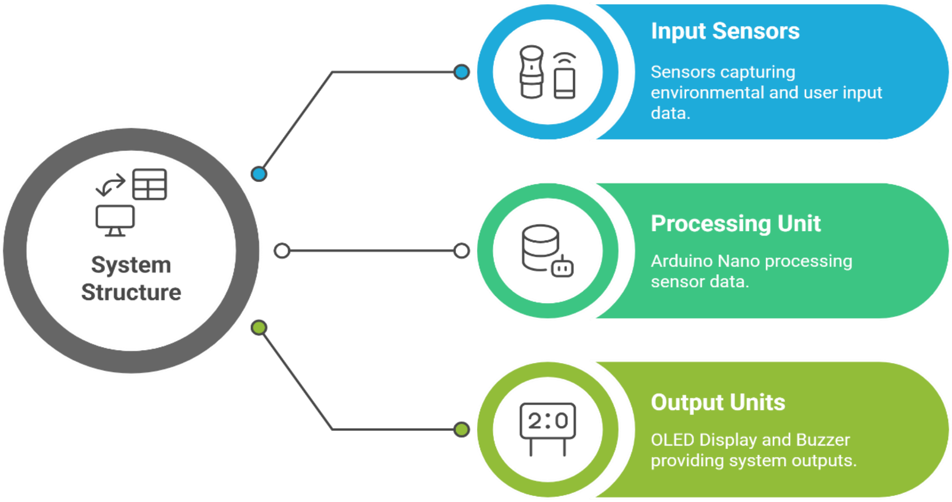

Fig 1: Unveiling the System's Structure

Figure 1: Block Diagram of the System. It shows the flow: Inputs (Sensors + User Controls) → Processing (Arduino Nano) → Outputs (Display + Audio)

The hardware connections pose as simple and efficient such that there would be minimum noise in the transmission of signals. The schematic is in detail displayed in the Circuit Diagram (Figure 2). The wiring is in the following manner:

- **LDR Sensors:** Linked to the Uniroyal input pins **A0, A1, A2,** and **A3** to measure the level of light intensity.
- **I2C Modules:** The OLED display as well as the **VL53L1X** laser sensor are based on the I2C communication protocol and are attached to the **SDA (A4)** and **SCL (A5)** lines.
- **Calibration Potentiometer:** Connected to analog pin **A6**.
- **Push Button:** Connected to digital pin **D2**. The code can then be used to allow the internal pull-up resistor to keep the HIGH signal stable when the button is open and the LOW signal when the button is closed.
- **LED Source:** Linked to digital pin **D3** by means of a **220 ohms** current limiting resistor.
- **Power Supply:** The components of the system are supplied by the power of the **5V** and **3.3V** outlets of the Arduino as needed by the logic of the particular module.

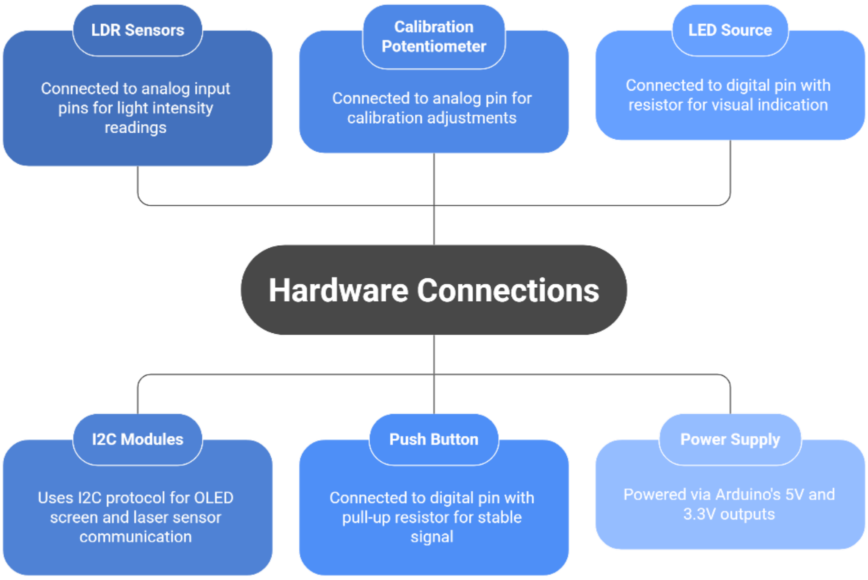

Fig 2: System Hardware Connections

Figure 2: Circuit Diagram of the circuit with particular pin connections: LDRs (A0-A3), I2C Bus (A4 / A5) and Digital I/O to be controlled.

6.3. Software Logic and Operation

This system is based on the code of C++ in the Arduino IDE. To guarantee the efficient performance, open-source libraries, including U8g2, which drives the OLED display, and VL53L1X, which drives the laser sensor, were used**.**

The working process (Algorithm) is as follows:

1. Calibration: The system reads the potentiometer value upon the startup. This establishes a dynamic threshold with which the intensity of the source is isolated by subtracting the ambient room light off the final reading.

2. Standby: The OLED display shows a "Ready" message, which waits to get the input of the user.

3. Trigger & Processing: Upon pressing the push button by the student, the Arduino will do the following:

- **Distance Measurement (r):** It requests a distance reading from the VL53L1X sensor (in cm).

- **Intensity Averaging (I):** The system makes 10 consecutive measurements of all the four LDRs (40 samples in total), removes noise, and averages the resulting intensity (I avg) to ensure reliability of the collected data.

4. Display: The processed findings are displayed on the screen within 5 seconds (in the following format: Dist: 15.2 cm | Int: 850).

5. Record & Repeat: The system goes to standby and the student can change the location of the source and repeat the procedure.

Table 1: Experimental Data (Results Table)

Distance r (cm)	Sensor Reading	Intensity (%)	Inverse Square $(1/r^2)$
19.0	716	70%	0.00277
19.9	614	60%	0.00252
20.7	511	50%	0.00233
21.2	409	40%	0.00222
21.8	307	30%	0.00210

7. Results and Analysis

In section 4.4 data were tabulated to show the relationship of distance (r) and intensity (I) and it was found that the intensity diminishes with distance. To confirm the law that ruled, two graphs were plotted on Excel:

1. Intensity vs. Distance (I vs r)

The decay of the intensity is as seen in Figure 3 shows the evolution of the graph. As the curve declines substantially when

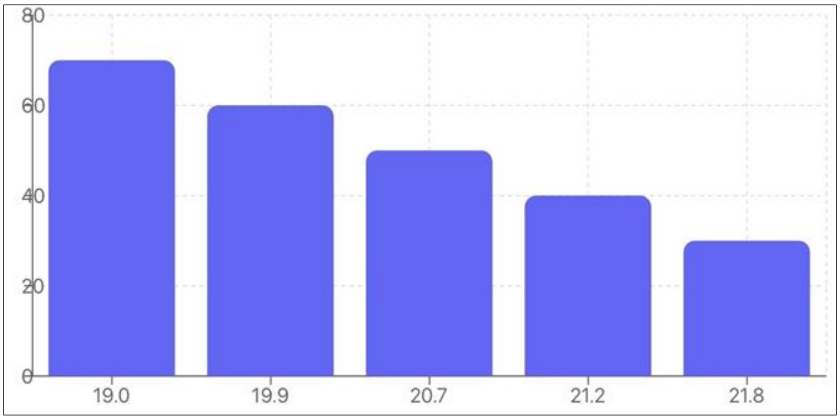

Fig 3: The sensor is made to move away and so on, proving the excessive attenuation of light energy with distance.

2. Intensity vs. Inverse Square (I vs 1/r^2)

This is the most significant graph. The intensity was plotted against the square of the distance. As in Figure 4, data points are in a definite linear trend. This straight line shows that the strength is directly proportional to the inverse square of the distance thus affirming the existence of the same.

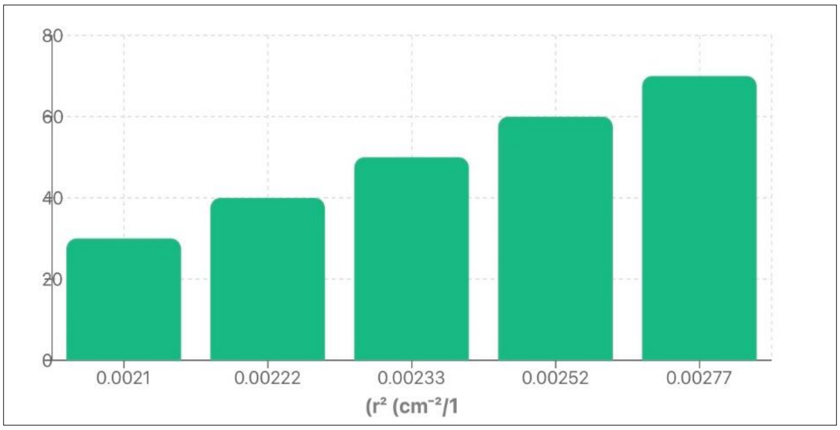

Fig 4: Inverse Square Law.

Statistical Note:
The linear relationship was as expected as the correlation coefficient between I and $1/r^2$ was more than 0.95.

Analysis

The interpretation is not very complex. Figure 3 depicts the way in which the light disappears very fast with distance increasing. The mathematical validation is presented in Figure 4; since the points are aligned in a straight rising pattern then it indicates that the theoretical model is accurate. This experiment transforms a complicated equation in physics to a visible form of reality that can be easily understood.

8. Discussion

The experimental findings using the proposed optical setup give a physical and quantitative realization of the law of inverse squares in an experimental setup which has a direct radiotherapy physics motivation. The fact that the intensity (I) versus 1 over the distance (1/r 2) has a strong linear correlation with a correlation coefficient of greater than 0.95 is an indication that the LEDLDR system acts much like a perfect point source in geometric fall-off. This implies that in even the simplest of teaching machines even minor movements in distance as the source is moved between 19.0 cm and 21.8 cm lead to great relativity of change in the measured intensity and reflect the dose-to-source-to-surface distance (SSD) sensitivity of clinical beams.

The conceptual findings can be correlated to the clinical findings presented by Sun et al. in their study of the robustness of VMAT plans [1]. In their work, small setup errors were shown to alter target coverage and dose distributions in a way that is ultimately rooted in geometric effects, including inverse-square behaviour. Likewise, the results of Havnen-Smith on setup tolerance in breast radiation therapy [2] demonstrate that modest positioning deviations can have a measurable impact on the dose received by both the planning target volume and surrounding tissues. The behaviour documented in our optical experiment thus provides a simplified, yet physically faithful, analogue of the same distance–dose sensitivity described in these clinical studies [1, 2].

Pedagogically, the device bridges a critical gap between abstract theory and constrained clinical practice. While students are usually taught the ISL as a mathematical relation, they rarely have the opportunity to conduct repeated, hands-on measurements over a wide range of distances under controlled conditions. The developed system allows them to do exactly this: they can acquire multiple data points, plot I versus r and I versus $1/r^2$, and see how small changes in r translate into large changes in I. In this way, the device operationalises the message of Sun et al. and Havnen-Smith—that precise setup and distance control are essential in radiotherapy—within a safe, low-cost laboratory exercise that can be integrated into routine teaching without using ionising radiation [1, 2].

Finally, the modularity of the Arduino-based design offers opportunities for future extensions. For example, students could be asked to deliberately introduce "setup errors" by misaligning the detector or tilting the source and then quantify the resulting deviations from the ideal inverse-square trend. Such activities would further strengthen the conceptual link between geometric accuracy, ISL behaviour and clinical dose delivery, reinforcing the importance of high-precision positioning in modern external beam radiotherapy as emphasised in [1, 2].

9. Conclusion

To sum up, the project was able to design and create a safe, low cost and interactive Inverse Square Law simulation system. We managed to close the divide between a concept of critical theoretical science and a dangerous clinical implementation of radiotherapy by using common electronic parts and the Arduino platform.

The system was experimentally validated in a strong manner. Precisely, the findings of the correlation between Intensity (I) and the Inverse Square of distance (1/r 2) had shown that there was almost a perfect fit of the theoretical formulation with a very small error margin.

Finally, this system provides a valuable educational tool that eliminates the risks of real radioactive sources. It is highly suitable to be integrated into Medical Physics laboratories as a practical exercise to demonstrate the dose–distance relationship and to analyze the effects of small variations in Source-to-Surface Distance (SSD).

10. References

1. Sun X, Guan F, Yun Q, Jennings M, Biggs S, Wang Z, et al. Impact of setup errors on the robustness of linac-based single-isocenter coplanar and non-coplanar VMAT plans for multiple brain metastases. J Appl Clin Med Phys. 2024;25(7):e14317. doi: 10.1002/acm2.14317
2. Havnen-Smith A. SU-E-J-71: Dosimetric impact of setup tolerance for breast radiation therapy with 3D surface imaging. Med Phys. 2012;39(6 Part 7):3668-9. doi: 10.1118/1.4734906
3. Shao H. Systematic setup errors for intensity modulated radiation therapy in the nasopharyngeal carcinoma: Effect on dose distribution. China Oncol. 2008;18(8).
4. Eyadeh MM, Weston MA, Juhasz J, Diamond KR. Translucent poly(vinyl alcohol) cryogel dosimeters for simultaneous dose buildup and monitoring during chest wall radiation therapy. J Appl Clin Med Phys. 2016;17(5):308-19. doi: 10.1120/jacmp.v17i5.6148
5. Nzabahimana J, Ndihokubwayo K, Mugabo LR. Teachers' experiences with the use of virtual laboratories in the teaching of physics in Rwandan secondary schools: A survey design. Afr J Res Math Sci Technol Educ. 2024;28(1):1-14. doi: 10.1080/18117295.2024.2361546
6. Razuck FB, Gonçalves G de L, de Sá LV. Use of augmented reality for demonstration of PET/CT and X-ray room to teaching medical physics in nuclear medicine. Rev Bras Fis Med. 2020;14:588. doi: 10.29384/rbfm.2020.v14.19849001588
7. Yevtushenko Y. Innovative teaching methods in medical and biological physics in higher education: Integration of pedagogical technologies and a scientific approach. Educ Pedagog Sci. 2024;3(187):47-59. doi: 10.12958/2227-2747-2024-3(187)-47-59
8. Çoban A, Çoban N. Using Arduino in physics experiments: Determining the speed of sound in air. Phys Educ. 2020;55(4):043005. doi: 10.1088/1361-6552/ab94d6
9. Singh R, Singh AK, Singhal S. Physics experiments using Arduino: Determination of the air quality index. Phys Educ. 2021;57(2):025013. doi: 10.1088/1361-

6552/ac3d22
10. Rahmat AD, Kuswanto H, Wilujeng I, Mat Daud AN. Local culture integration in physics experiments: Exploring Angklung with Arduino-enhanced frequency measurement. TEM Journal. 2024;13(2):1248-55. doi: 10.18421/TEM132-38

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