Arduino-Assisted Buoyancy Demonstration Tool for Physics Learning in High School

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Abstract

This study aims to produce a product in the form of a physics teaching aid for secondary school on the topic of Archimedes' principle. The developed teaching aid consists of an Arduino as the main controller, a mass sensor to detect changes in the mass of the submerged object, and a beaker attached to acrylic and supported by a stand. The device can automatically record mass changes of the load and the measuring beaker. The research method employed is R&D with a 4D model, consisting of four stages: Define, Design, Develop, and Dessimination. The variable used is the variation in the depth of the submerged object. The Arduino output is presented in the form of data and graphs using Microsoft Excel. The product has undergone material and media validation tests with average percentages of 90.67% and 100%, respectively. Based on the results, it can be concluded that the Archimedes' principle teaching aid using Arduino is valid as a supporting medium for physics learning. The limitation of this study is the absence of the dessimination stage involving teachers and students. However, this study successfully produced a teaching aid that can be used to support the physics learning process.

Keywords: *physics teaching aids; Bouyancy; Arduino; load cell*

1. INTRODUCTION

Understanding the concept of buoyancy is a significant challenge in physics education at the secondary school level (Gao et al., 2023). This concept involves various aspects of physics such as density, gravity, the volume of liquids, and hydrostatic pressure, which are all interconnected. Unfortunately, students often find it difficult to visualize these interactions between variables because the presentation tends to be abstract and theoretical (Stromme & Mork, 2020). Additionally, the still-dominant conventional teaching methods, which primarily consist of passive lectures and demonstrations, are often not effective enough in building students' deep conceptual understanding. Therefore, a more contextual and hands-on learning approach is needed so that students can construct their own understanding of the concept of buoyancy.

The development of microprocessor technology, such as Arduino, opens up significant opportunities for designing affordable and easy-to-operate interactive teaching aids (Feger et al., 2022). Arduino is an open-source electronic platform that can be programmed to control various sensor and actuator components (Corno & Mannella, 2023). With its flexibility, Arduino has great potential to be used as a base for developing physics demonstration tools that can present data in real-time, interactively, and accurately (Fonseca-Campos et al., 2022). Integrating Arduino into learning allows teachers and students to explore physics concepts not only through theory but also through data-driven experiments, making the learning experience more enjoyable and meaningful (Schnider & Hömöstrei, 2024). The use of Arduino in the context of buoyancy learning provides students with the opportunity to directly observe changes in force as the depth and mass of the submerged object change (Cámara-Zapata et al., 2023).

On the other hand, 21st-century education demands the integration of the STEM (Science, Technology, Engineering, and Mathematics) approach into the learning process. The development of Arduino-based teaching aids on the topic of buoyancy indirectly supports the implementation of this approach, as it involves engineering design, programming (technology), physical analysis (science), and numerical data processing (mathematics) (Marín-Marín et al., 2024). With this approach, students are not only required to understand the concept of buoyancy but are also encouraged to think critically, solve problems, and work collaboratively in conducting experiments (Zou et al., 2023). This aligns with the Pancasila student profile, which is expected to possess 21st-century competencies such as reflective thinking, innovation, and scientific literacy skills (Dare et al., 2021).

Research by several education experts indicates that students who learn using visual aids and independent experiments are better able to understand the relationships between variables and explain phenomena scientifically. In the context of buoyancy, props that can demonstrate changes in force as an object is submerged in a liquid will provide a more realistic and easier-to-understand picture than simply using illustrations on a whiteboard (Bajo et al., 2020). Therefore, the development of a buoyancy demonstrator integrated with sensor and microcontroller technology is a relevant innovation that meets the needs of the times.

In the high school environment, the availability of inexpensive, portable, and easy-to-use teaching aids is an important factor in supporting the learning process (Moca & Badulescu, 2023). This Arduino-assisted buoyancy demonstrator was designed by utilizing weight and depth sensors connected to a microcontroller to digitally measure and display buoyancy (Elkolali et al., 2022). The data obtained can be observed directly on the LCD screen or transferred to a computer for further analysis. This approach not only enriches the learning experience but also trains students' scientific skills in terms of observation, analysis, and data interpretation.

Based on the explanation above, research is needed on learning media in the form of visual aids that can provide a physical representation to clarify the concepts presented by educators to students. Therefore, in this study, a buoyancy force demonstration tool was developed using an Arduino board and load cell to support Physics learning in high school. Through this tool, any data generated can be observed and analyzed effectively.

2. RESEARCH METHODOLOGY

The research method used is the Research and Development method to develop a research product in the form of high school physics teaching aids using Arduino on the topic of buoyancy. The research procedure for developing the product is the same as the 4D research and development model, namely:

Define

The definition stage includes formulating an introduction by identifying the problem or gap and the potential causes of the gap. The activities that need to be analyzed are analyzing the current curriculum, learning objectives and competencies to be achieved, the type of material or topics presented, the target audience or students, and the method of delivery.

Design

The planning stage is carried out by determining goals, assessment instruments, exercises, content, and analysis related to learning materials, lesson plans, and media selection. The design activity begins by outlining the components of the teaching aid to be developed,

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followed by structuring the product's system. This design will be the foundation for further development. The design of the props to be developed is shown in Figure 1. The explanation of the parts of the developed tool is outlined in Table 1.

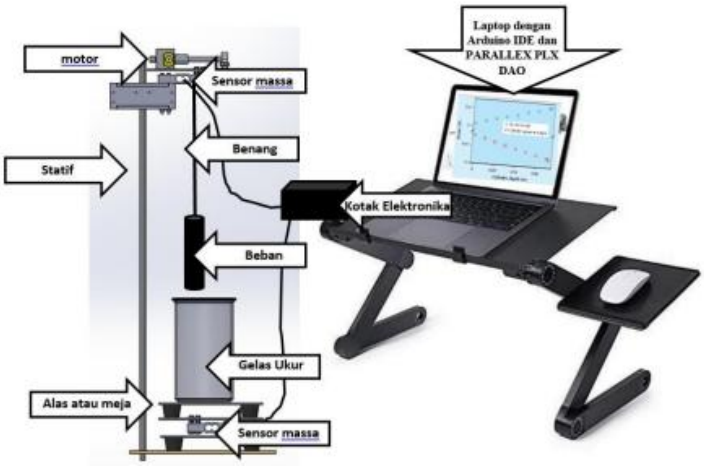

Figure 1. Design of the Teaching Aid to be Developed

Table 1. Components of The Teaching Aid

No.	Equipment Components	Description
1.	Beaker	Storing the fluid to be tested
2.	Static	Supporting the components of the tools used in the teaching aid
3.	Mass sensor	Mass change signal detector for both the load and the beaker
4.	DC Motor	Moving loads (raising and lowering loads)
5.	Table	Supporting the beaker
6.	Burden	Observed object
7.	Thread or rope	Supporting the load
8.	Electronic box	Storing electronic components and Arduino
9.	Laptop devices	Saving data

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Development

The development stage includes preparing materials for building the buoyancy aid. The necessary tools and materials include an Arduino Uno, a Load Cell sensor, a Load Cell Amplifier (HX711), an electric motor, a beaker, a stand, a laptop/personal computer, weighted loads, cables, and connectors. The block diagram of the demonstration tool system is shown in Figure 2. Based on the block diagram in Figure 2, the developed system consists of two load sensors, each equipped with an HX711 driver as an amplifier and ADC converter. The upper load sensor is connected to an Arduino Micro, while the lower load sensor is connected to an Arduino Uno as the main controller, which will convert the sensor input and process it to produce a mass value. The Arduino Uno also receives input from calibration, up, and down push buttons for manual adjustment, sends output data to the LCD for displaying measurement results, and controls the L298 Motor Driver, which then regulates the direction and speed of the DC Motor. Based on sensor data and user input, the Arduino Uno controls the L298 Motor Driver, which then regulates the direction and speed of the DC Motor.

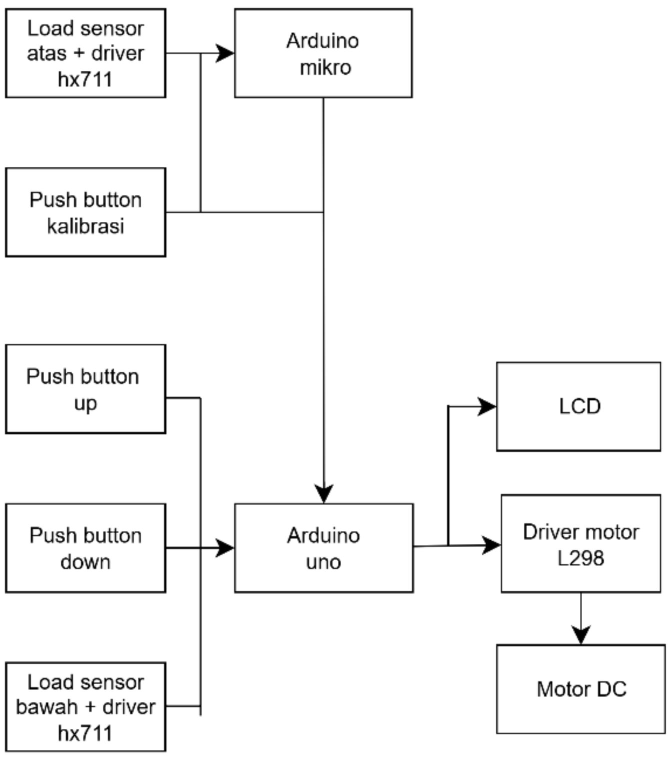

Figure 2. System Block Diagram of the Teaching Aid

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Next, we move on to the product creation or development stage until it can be used to collect the necessary data. To align what students need with what is developed, a validation test is conducted. The validation test is administered to content experts and media experts by having them assess the product using a questionnaire instrument to understand the validity of the developed teaching aid.

Disseminate

The dissemination stage was not carried out in this study. This is because:

(1). Limited research time

(2). The school did not provide time for research

(3). The sample tested was insufficient

Data Collection Techniques

At the stage of testing the props, measurements were taken repeatedly 5 times under each condition. The data obtained was then processed using equation (1-3) to determine the average value ($\bar{\rho}$), standard deviation (s), and relative error ε_r. The research data collection technique was carried out using research instruments in the form of questionnaires. The chosen questionnaire is a closed-ended questionnaire with a calculation scale using a Likert scale. The questionnaire consists of product evaluation and product implementation questionnaires, which were given to content matter expert validators and media expert validators.

$$\bar{\rho} = \frac{\Sigma\rho}{n} \tag{1}$$

$$s = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\rho_i - \bar{\rho})^2} \tag{2}$$

$$\varepsilon_r = \frac{s}{\bar{\rho}} \tag{3}$$

Data Analysis Techniques

The validity of the teaching aid was determined using two data analysis methods: qualitative and quantitative. Qualitative data consists of responses, criticisms, and suggestions

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provided by validators regarding the research product. Quantitative data is the assessment obtained from the validation of the teaching aid by validators using a 5-point Likert scale. The score interpretation is calculated based on the research score for each assessment aspect using equation (4). Data interpretation at each level is according to Table 2.

$$\%score\ interpretation = \frac{\Sigma\ score\ earned}{\Sigma\ maximum\ score} x\ 100\% \tag{4}$$

Table 2. Data Interpretation

No.	Percentage	Description
1.	$20\% - 36\%$	Not valid at all, and therefore should not be used
2.	$37\% - 52\%$	Invalid, not recommended for use as it requires major revisions.
3.	$53\% - 68\%$	Quite valid, usable but needs minor revisions.
4.	$69\% - 84\%$	Valid, or usable with or without revision
5.	$85\% - 100\%$	Very valid, or can be used without revision.

3. RESULTS AND DISCUSIONS

Results

This research resulted in a product in the form of a demonstration tool to facilitate data collection in buoyancy experiments on liquids. The teaching aids developed according to the design in Figure 1, while the appearance of the teaching aid set is shown in Figure 3. Figure 3 shows an electronic box equipped with an LCD, a tripod frame with a load cell attached, and computer equipment.

DOI : doi.org/10.21009/parameter.372.03

Figure 3. Experimental Setup of Teaching Aid

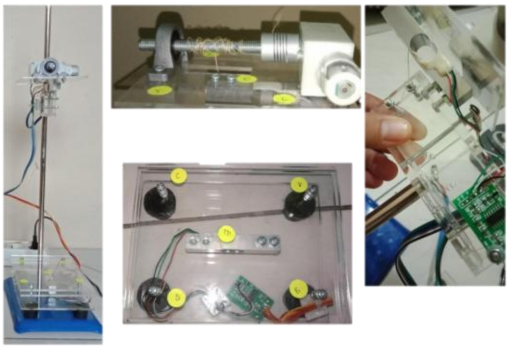

Figure 4. Tripod frame with mass sensor installed

The tripod frame shown in Figure 4 consists of several parts: (1) The upper mass sensor frame is made of acrylic with the mass sensor, amplifier, and motor attached; (2) The lower mass sensor frame is made of acrylic with 4 rubber feet attached to the mass sensor, amplifier, and motor. The function of the lower sensor frame is to serve as a table for measuring the mass of the beaker; (3) The tripod serves as the path for the upper mass sensor frame and the base for the lower mass sensor; (4) The DC motor is connected to an Arduino programmed to raise and lower the load attached to the thread wound around the motor; (5) The thread serves as the point of attachment for the load that will be dipped; (6) The sensors are installed on the upper and lower sensor frames, and the mass sensor is used to send analog signals to the amplifier to be converted into digital signals that are then read by the Arduino as data on the mass of the immersed object or the mass of the beaker. This upper mass sensor frame can be raised and lowered to adjust the height of the beaker below.

DOI : doi.org/10.21009/parameter.372.03

Figure 5. Electronics Box

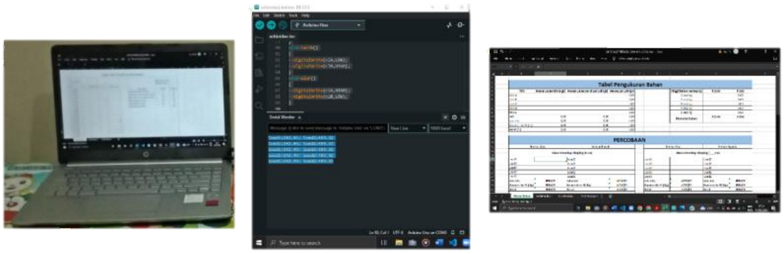

Figure 6. Device

Figure 7. Other Laboratory Equipment (Weights, Beakers, Liquids)

Figure 5 shows an electronic box in the form of a white box. The electronic box contains electronic circuits equipped with an Arduino Uno R2 and an Arduino Pro Micro, a power supply, and an L298 motor driver. It functions as the brain or control center of the system. On the front panel of this electronics box, there are 4 buttons and an LCD screen. The yellow button functions as a calibration button to keep the sensor stable at 0.00 grams. The Red Button functions to rotate the motor and simultaneously wind the thread clockwise, thus raising the load. The Blue Button functions to rotate the motor counterclockwise, causing the thread to unwind and the load to lower. The green button functions to transmit the value read by the

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mass sensor to the Arduino IDE screen. There is a USB cable to connect the device to a laptop or PC. The LCD screen detects the mass value from both sensors. On the back panel, there is a power button, a power supply cable, and a CB connector connecting the upper and lower mass sensor frames.

The computer device used is a laptop, as shown in Figure 6. The laptop has software installed, including Arduino IDE and Microsoft Excel. Arduino IDE is used to program the system to generate upper and lower mass data for each submerged load depth, which will then be displayed on the Arduino IDE serial monitor. Microsoft Excel functions as a data processor from the Arduino IDE serial monitor, displaying data in tables and graphs for analysis. The research was conducted using a set of weight plates, a 500 ml beaker as a container for the liquid, and a fluid (mineral water) as shown in Figure 7. The weights used each had a mass of 242.51 grams. The characteristics of the weights are shown in Table 3. Meanwhile, the characteristics of the beaker are shown in Table 4.

Table 3. Load Characterization

High load per piece	**h (cm)**	**h (m)**
1 piece	0.80	0.01
2 piece	1.60	0.02
3 piece	2.40	0.02
4 piece	3.20	0.03
5 piece	3.90	0.04
Load diameter	**d (cm)**	**d (m)**
	3.10	0.03

DOI : doi.org/10.21009/parameter.372.03

Table 4. Characteristics of Beakers

Point	Mass of the Beaker (gr)	Mass of a Glass Filled with Liquid (gr)	Mass of Liquid Matter (gr)
Point A	159.67	533.35	373.68
Point B	159.50	534.04	374.52
Point C	159.76	533.58	373.82
Point D	159.95	534.39	374.44
Point E	159.70	533.80	374.10
n = 5	798.58	2669.14	1870.56
Average	159.72	533.83	374.11
Conversion to SI (kg)	0.16	0.53	0.37
Weight (N)	**1.57**	**5.23**	**3.67**

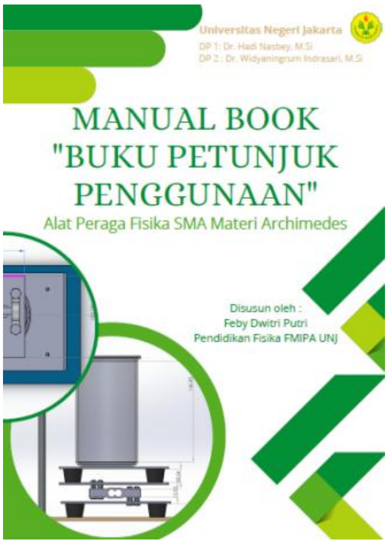

Figure 8. Book Cover View of the User Manual

As a support for using teaching aids as a learning medium, student worksheets (LKPD) and instruction manuals were created, as shown in Figure 8. The working principle of the demonstration tool is shown in Figure 9. After connecting to the power supply and laptop, as well as the Arduino IDE application displaying the Arduino IDE serial monitor on the laptop. The mass sensor will start counting from 0, with the display on the electronic box LCD showing 0.00 grams when the yellow button is pressed. Weights were hung on the thread wrapped around the motor, and the beaker filled with liquid was placed on a table equipped with a mass sensor. Then, the green button was pressed to transmit the mass value detected by the mass sensor. Once 5 data points have been entered, the transmit button is pressed again to stop scanning for data. The data generated is entered into the table for disc 0. This is repeated for 1 dipped disc, 2 dipped discs, 3 dipped discs, 4 dipped discs, until all discs are submerged/dipped in the liquid. The mass sensor will begin to detect the applied load, resulting in a reaction to the metal element on the mass sensor, causing elastic deformation to occur. The force generated by the strain is then converted into an electrical signal by the strain gauge, and the Arduino will issue a transmit command when the transmit button is pressed so that the detected signal is recorded on the Arduino IDE serial monitor. The data obtained from the sensor system is an interpretation of the programming data in the Arduino IDE that was previously uploaded to the Arduino UNO processor. This data interpretation is in the form of the position of the mass value in grams from both mass sensors. The data display from the Arduino IDE serial monitor transferred to Excel on the laptop is shown in Figure 10.

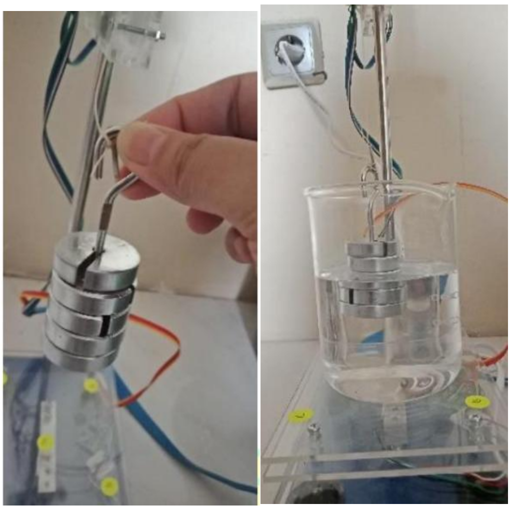

Figure 9. Working Principle of the Teaching Aid

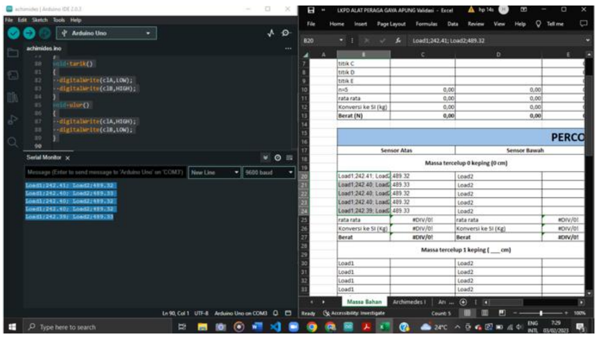

Figure 10. Data from the Arduino IDE serial monitor transferred to Excel

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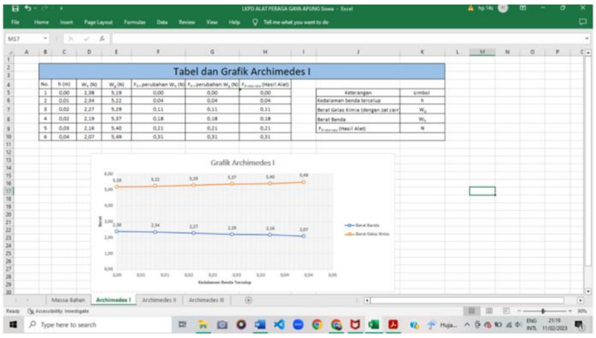
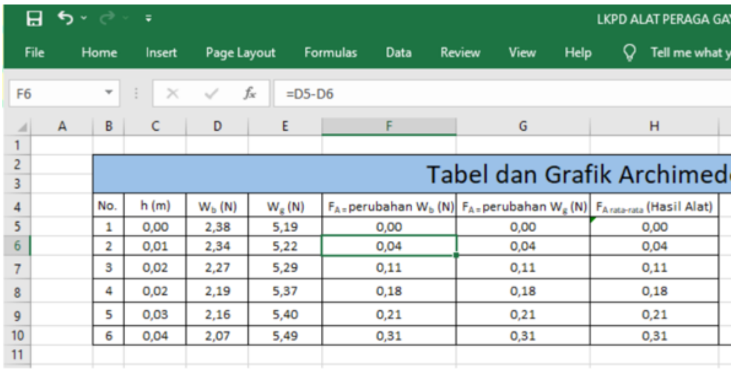


Figure 11. Excel View of the Graph Results of an Experiment



Tabel dan Grafik Archimed

No.	h (m)	W_b (N)	W_g (N)	F_A = perubahan W_b (N)	F_A = perubahan W_g (N)	$F_{A\ rata\text{-}rata}$ (Hasil Alat)
1	0,00	2,38	5,19	0,00	0,00	0,00
2	0,01	2,34	5,22	0,04	0,04	0,04
3	0,02	2,27	5,29	0,11	0,11	0,11
4	0,02	2,19	5,37	0,18	0,18	0,18
5	0,03	2,16	5,40	0,21	0,21	0,21
6	0,04	2,07	5,49	0,31	0,31	0,31

Figure 12. Using Formulas in Excel

From the Excel data, a graph can be created to analyze the changes in the weight of the submerged object and the beaker. The changes from one point to another, both in the beaker and the submerged object, represent the Archimedes force/buoyant force generated based on the volume of the submerged object, as shown in Figure 12.

In the learning process, the availability of data results in the form of graphs and tables aims to make it easier for students to analyze data and directly see or visualize physical phenomena. With this strategy, the advantage provided in the development of this teaching aid is not only the automation of the tool, but also simultaneously stimulates students' skills and creativity in using computer devices, especially their proficiency in using Microsoft Excel software.

Product Validation Test Results by Content Experts

The product validation test by subject matter experts involved a physics lecturer from Universitas Negeri Jakarta. The purpose of this validation test is to determine the validity of the Archimedes' principle teaching aid product from a material perspective. Table 5 shows the data obtained from the content expert validation test results.

Table 5. Results of Material Expert Validation Test

No	Aspek Penilaian	Skor	Interpretasi
1.	Kesesuaian Isi	100%	Sangat Valid
2.	Kesesuaian Konsep	92%	Sangat Valid
3.	Kesesuaian Desain	80%	Valid
Rata-rata Keseluruhan Aspek		90.67%	Sangat Valid

From the data obtained from the material validation test results, the average percentage achievement for all aspects was 90.67%. This is categorized as Very Valid for use as a visual aid in the high school physics learning process for Archimedes' principle. Notes on the validation stage by subject matter experts for the developed researcher and props are that improvements can be made by creating a user interface that makes the operation process easier.

Product Validation Results by Media Experts

Product testing by media experts involved one physics lecturer from the Faculty of Mathematics and Natural Sciences, Universitas Negeri Jakarta. The purpose of this validation test is to determine the validity of the developed product so that it can be a learning aid or medium that supports the teaching and learning process. The validation results obtained are summarized in Table 6. From the data obtained from the media validation test results, the average percentage achievement for all aspects was 100%, categorized as Very Valid for use as a visual aid in the high school physics learning process for the topic of buoyancy without revision. Based on the assessment results from the media expert validator, there are notes for further research: the scale of the thread winding should be reduced and the weight made solid or a single unit.

Table 6. Results of Media Expert Validation Test

No	Assessment Aspects	Score	Interpretation
1.	Content Relevance	100%	Very Valid
2.	Interactivity	100%	Very Valid
3.	Concept Alignment	100%	Very Valid
4.	Design Suitability	100%	Very Valid
5.	Effectiveness and Efficiency	100%	Very Valid
	Overall Average Aspect	100%	Very Valid

Discussion

The development of an Arduino-assisted buoyancy demonstrator in this study aims to address the need for innovative, interactive, and contextual learning media, particularly in the static fluids material within high school physics lessons. The concept of buoyancy is often considered abstract by students due to limitations in visualization and its connection to real life. By combining Arduino microcontroller technology and an experimental learning approach, this tool provides a concrete visualization of Archimedes' principle.

Integration of Physics and Technology Concepts

This instrument not only provides visual observations of floating or sinking objects but also includes sensors capable of quantitatively measuring important parameters such as density, object volume, and buoyancy. Arduino acts as a real-time data processor and display, enabling students to independently perform measurements, data processing, and analysis. Thus, learning is no longer centered on memorizing concepts, but rather is oriented towards a scientific process that combines direct observation, data collection, and conceptual reflection. This aligns perfectly with the demands of the Merdeka Curriculum and STEM-based learning, which encourages interdisciplinary integration and the strengthening of 21st-century skills such as critical thinking and problem-solving.

Significance of the 4D Model in Media Development

The use of the 4D model (Define, Design, Develop, Disseminate) provides a systematic and valid framework for the development process. At the Define stage, the need for representative floating-style learning media was identified, including the limitations of conventional props, which are only demonstrative without quantitative data. The Design and

Develop phase focuses on designing an Arduino-based prototype that can be used in school laboratories, considering affordability, ease of assembly, and safety aspects. This is where the principles of simple engineering are introduced, linking physics with the practice of microtechnology. The validation results from media experts and content experts indicate that this approach is not only technically feasible but also conceptually sound. Validation by media experts (90.67%) indicates that this media is excellent in terms of appearance, interactivity, and the use of Arduino. Meanwhile, validation by content experts (100%) confirms that this media is scientifically sound and aligns with the objectives of physics learning.

This tool supports exploratory and investigative learning, two approaches proven to enhance students' conceptual understanding. When students are directly involved in experiments using tools that present digital data, they are encouraged to ask questions, compare results, and draw conclusions. This aligns with the inquiry-based learning approach, which is a key characteristic of contemporary science education. Thus, the use of technology like Arduino opens up opportunities to incorporate basic computational and electronic elements, enriching students' learning experiences and facilitating interdisciplinary collaboration (science, IT, and even mathematics). Learning is becoming more multidisciplinary, allowing for the strengthening of cross-disciplinary thinking skills. Although the product has been validated and declared highly valid, its use in the classroom still requires the guidance of a teacher competent in technology. Therefore, it is important for teachers to receive training in the use of Arduino and the integration of digital media in learning. Additionally, this tool has the potential for further development by adding data logging features or Bluetooth/Wi-Fi integration, allowing experimental data to be accessed and analyzed via students' mobile devices or computers, thus strengthening the information technology aspect of physics learning.

4. CONCLUSION

Based on the data from the research findings and discussion, it can be concluded that product development has been carried out, resulting in a valid Arduino-based high school physics teaching aid for buoyancy material that can be used and implemented as a learning support tool. Given the limitations of teaching aids and their distribution, further development is needed to make the experiments more specific and accurate. Additionally, further research is necessary to determine the effectiveness of the developed teaching aids in physics learning in schools. By conducting product readability tests with both teachers and students as an implementation of the dissemination stage.

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