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Innovation and Validation of Relative Permeability Experimental Tools Using Metal Materials as a Medium for High School Physics Education

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Abstract: This research is motivated by the limitations of physics learning media in high schools, especially in magnetism materials, which are abstract and difficult to understand without the support of appropriate experimental tools. This condition hinders students' ability to relate theory to real phenomena. This research aims to develop and test the feasibility of a relative permeability experiment tool for metal materials as a high school physics learning medium. This tool is designed to help students understand the concept of magnetism, especially the relationship between the number of turns, voltage, current strength, magnetic induction, and relative permeability in various types of metals. The research method used is research and development (R&D). The test results show that steel has an average relative permeability value (μr) of 3.9, which indicates strong ferromagnetic properties, while iron has an μr of around 1.4 with moderate ferromagnetic properties. Aluminum with an average μr of 1.0 and brass, with an average μr of 0.7 are classified as non-ferromagnetic. Thus, this test tool can clearly distinguish ferromagnetic and non-ferromagnetic materials based on their relative permeability values. Validation was conducted by three experts, with an average value of 3.77, which is considered very high. Furthermore, a practicality test involving 16 high school physics teachers showed a very high practicality category. Based on these results, it can be concluded that the developed relative permeability experiment tool is valid, practical, and suitable for use as a physics learning medium to improve students' understanding of the concept of magnetism.

Keywords: High school; Innovation and validation; Metal materials; Physics learning media; Relative permeability experimental tools

Introduction

The development of science and technology in the 21st century demands innovation in various fields, including education (Mardhiyah et al., 2021). Education, particularly at the senior secondary level, plays a crucial role in shaping a young generation capable not only of understanding theoretical concepts but also of possessing practical skills, critical thinking skills, and creativity to face global challenges. Physics, as a high school subject, is often considered difficult by students due to its abstract nature, its richness in symbols, and its requirement for high mathematical skills (Mashudi, 2021). Data from the 2022 Programme for International Student Assessment (PISA) show that the average science score of Indonesian students is still below the OECD average, at 388 points compared to 489 points. This indicates that mastery of scientific concepts, including physics, remains a serious problem that needs

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to be addressed immediately through innovative learning approaches (Ernidawati et al., 2025).

One of the causes of students' poor understanding of physics is the limited learning media available in schools (Rosyid et al., 2024; Basyori & Herdiana, 2024). According to a 2021 survey by the Research and Development Agency (Balitbang) of the Ministry of Education, Culture, Research, and Technology, approximately 40% of secondary schools in Indonesia still lack adequate laboratories for science experiments, including physics. Even in schools that do have laboratories, not all are equipped with standardized and optimally functioning experimental equipment. This situation often results in physics learning being conducted theoretically, without the support of real-world practice. As a result, students are less able to connect abstract concepts with everyday phenomena they encounter around them (Yuliawati et al., 2023).

One of the important topics in the high school physics curriculum is the concept of magnetism, specifically the relative permeability of metallic materials (Sari et al., 2024). This concept discusses how certain metallic materials can strengthen or weaken the magnetic field around them, which is a fundamental phenomenon in modern technological applications, such as transformers, electric motors, generators, and other electromagnetic devices (Astuti et al., 2021). Unfortunately, this topic is often considered difficult by students due to its abstract nature and the lack of simple experimental media that can be used to directly demonstrate the phenomenon. Teachers usually explain it only explain using illustrations or animations from textbooks or digital media, so students do not gain real-world experience in observing and proving the principles of relative permeability (Erdinawati et al., 2023).

This phenomenon is exacerbated by the fact that Indonesian students' practical science skills are still relatively low. According to research conducted by UNESCO (2021), only 25% of Indonesian students demonstrate good scientific experimental skills, while the remainder rely more on theoretical memorization. This indicates a gap between the competencies expected in the Independent Curriculum, which emphasizes discovery and project-based learning, and the reality of limited infrastructure in the field. Therefore, efforts are needed to develop learning media that are innovative, contextual, affordable, and easy to use by both teachers and students, so that physics learning objectives can be optimally achieved (Mu'minah, 2021).

Permeability is a fundamental material property that describes a material's ability to allow fluids or fields to pass through it. In a general context, the term permeability is used in the study of both porous media (such as reservoir rocks, coal, and cementitious materials) and magnetic materials (such as ferrite, permalloy, and metal-based composites). The concept of relative permeability emerged to compare the ability of a material under certain reference conditions, both in multiphase fluid flow and in its magnetic response to an external field (Hamilton, 2015; Youssef et al., 2024).

In petroleum engineering and geology, relative permeability plays a crucial role in explaining the distribution of fluid phases (water, oil, gas, or CO_2) in porous media. This permeability is not solely determined by absolute permeability but is also influenced by saturation conditions, rock heterogeneity, and hysteresis phenomena (Lan et al., 2024). Early studies on reservoir rocks demonstrated that relative permeability significantly determines the efficiency of water and gas injection in enhanced oil recovery (Zhang et al., 2015). Recent research has extended this concept to the context of carbon capture and storage (CCS), which requires an understanding of the relative permeability of CO_2 gas in low-porosity rocks (Bai et al., 2020). Even in unconventional materials, such as coal and tight sandstone, the relationship between electrical properties and relative permeability can be used to predict fluid flow (Zhao et al., 2022).

Mathematical models have also been developed to explain variations in multiphase flow at different scales. Upscaling models have been developed to allow laboratory experimental results to be applied to larger reservoir scales (Sedaghat et al., 2020). Furthermore, factors such as fluid distribution within pores, media roughness, and temperature have become increasingly important aspects that are receiving growing attention (Zeng et al., 2019). In practice, relative permeability properties can be modified using polymer additives or nanoparticles to control fluid movement, as in chemical injection in carbonate reservoirs (Qin et al., 2020).

In magnetic materials science, relative permeability describes a material's ability to respond to a magnetic field. Highly permeable materials are widely used in the manufacture of transformers, magnetic shields, sensors, and modern electromagnetic devices. Magnetic permeability depends on microstructure, crystal orientation, temperature, operating frequency, and even magnetostriction phenomena (Li et al., 2025; Huang et al., 2024).

Several recent studies have focused on the development of magnetic composite materials capable of combining high permeability with low energy loss, such as Fe-Si, $FeSiAl/MoS_2$, and anisotropic fillers in metal-based composites (Koo et al., 2023; Zhu et al., 2022). At the micro and nanoscale, measurements have been performed on amorphous microwires using the antenna resonance method (López-Domínguez et al., 2017) and on magnetorheological fluids for dynamic applications (Lo Sciuto et al., 2022).

In addition to material development, permeability measurement techniques have also undergone significant progress. A Rayleigh-based method was used to measure the permeability of permalloy in very weak fields (Sun et al., 2022), while a harmonic cavity resonance technique was introduced for measurements at gigahertz frequencies (Yamaguchi et al., 2023). A magnetic induction spectroscopy approach even allows for mapping the spatial distribution of relative permeability (Drnovšek et al., 2009). Operating conditions such as transverse magnetic fields (Syas' ko et al., 2019) and particle orientation due to flow in composites (Fiske et al., 1997) have been shown to influence permeability properties.

In this context, research and development (R&D) related to the innovation and validation of a metal relative permeability experiment tool becomes highly relevant and urgent. This experimental tool is expected to bridge the gap between theory and practice by providing a simple yet effective means of demonstrating how different metals differ in their ability to conduct magnetic fields. Using this tool, students can conduct direct observations, collect data, analyze results, and draw scientific conclusions. This process will increase student engagement in learning, foster curiosity, and hone critical thinking and problem-solving skills.

Several previous studies have developed physics learning media based on simple experimental tools. Arduino-based electromagnetic learning media have also shown improvements in students' experimental skills. However, most of these studies have focused on the electrical and wave aspects, while the relative permeability of metallic materials has not been widely explored. This topic, however, has significant potential for development due to its direct relevance to everyday life and industrial technology applications (Hartini et al., 2022).

Another gap in previous research is the lack of rigorous validation of the experimental tools developed. Some studies have stopped at a limited trial stage without adequately testing the instrument's validity, including in terms of materials, media, and construction. This makes the tools difficult to replicate or widely adopt by other schools. Furthermore, the test population in previous studies was often limited to a single class or school, limiting the generalizability of the results.

This research aims to fill this gap by innovating in the development of a simple, economical, and suitable experimental tool for the relative permeability of metal materials for high school physics learning. Furthermore, this research emphasizes validation by subject matter experts, media experts, and educational practitioners to ensure the feasibility and effectiveness of the developed tool. Trials will be conducted on several groups of students using a systematic R&D design to provide robust empirical data on the tool's quality. Thus, this research not only produces a new product but also enriches the R&D research methodology in the field of physics education.

The urgency of this research is also driven by global trends in 21st-century education that emphasize hands-on and inquiry-based learning. The National Research Council (2020) emphasizes that effective science learning must engage students in real-world investigations, rather than simply passively receiving information from teachers or textbooks. By providing experimental tools for the relative permeability of metals, students can design experiments, measure physical quantities, compare data, and construct their own knowledge through direct experience (Harian, 2024). This aligns with the Merdeka Belajar (Freedom to Learn) philosophy currently implemented in Indonesia, which emphasizes independence, collaboration, and experience-based competency mastery.

This research is expected to provide significant theoretical and practical contributions. Theoretically, this research will enrich the literature on the development of physics learning media with a focus on aspects of magnetism, particularly relative permeability. This contribution is important because there is still a lack of research discussing the development of simple tools for this material. Practically, this research will provide an alternative solution for high school teachers who often face limited laboratory facilities. The developed tool is expected to be widely used in various schools at an affordable cost and with simple procedures, thereby improving the quality of physics learning in Indonesia more evenly.

The main problems that form the basis of this research can be summarized as follows: (1) low student understanding of physics concepts, especially magnetism, due to its abstract nature and lack of experimental media; (2) limited laboratory facilities in many secondary schools which cause science practices to be rarely carried out; (3) minimal previous research that develops simple experimental tools for the topic of relative permeability of metal materials; and (4) lack of comprehensive validation in previous research on developing experimental tools. The challenge faced is how to design simple, inexpensive, yet valid and effective experimental tools to improve students' conceptual understanding.

Considering these issues, this study aims to develop and validate an experimental tool for the relative permeability of metal materials as a medium for high school physics learning. Validation was conducted through expert testing and limited student trials to ensure the tool's quality in terms of materials, media, and practicality. This study also aims to determine the extent to which this experimental tool can improve students' conceptual understanding of magnetism, particularly relative permeability.

The benefits of this research can be divided into two categories. First, theoretical benefits, namely contributing to the development of experimental-based physics learning theory and enriching R&D research references in the field of science education. Second, practical benefits, namely providing concrete solutions for teachers and schools in providing alternative learning media that are effective, affordable, and easy to use. Furthermore, this research can also inspire further innovation in the development of simple experimental tools for other physics topics.

This research is expected to be a concrete step in improving the quality of physics learning in high schools. The innovation of the relative permeability experiment tool for metal materials not only addresses the limited laboratory facilities but also encourages the development of a young generation with a strong understanding of science, strong practical skills, and high competitiveness in the era of globalization.

Method

This study uses a Research and Development (R&D) approach that is oriented towards developing educational products in the form of an experimental tool for the relative permeability of metal materials to be used as a medium for learning physics at the high school level. The R&D approach was chosen because it is in accordance with the research objectives, namely to produce an innovative product while testing its validity, practicality, and effectiveness in the learning context. The development model used is ADDIE (Analysis, Design, Development, Implementation, Evaluation), because this model has systematic and structured stages so that it can produce products that are in accordance with the objectives, namely to create an effective and efficient measuring instrument (Mulyatiningsih, 2016; Rahmaris & Ratnaningsih, 2022).

The ADDIE model consists of five stages, namely: (1) Analysis, which aims to identify learning needs related to the concept of relative permeability and the limitations of available practical media; (2) Design, which involves creating an initial design of a measuring tool that includes the selection of test materials, sensor systems, magnetic field mechanisms, and supporting electronic components; (3) Development, which involves producing a prototype of the tool followed by validity testing by experts, empirical testing, and practicality testing; (4) Implementation, in the form of limited trials in practical activities to determine the effectiveness of the tool in learning; and (5) Evaluation, which is carried out to assess the quality and effectiveness of the resulting product (Nurhayati, 2022).

However, this research only reached the development stage, which includes tool creation, empirical testing, validity testing, and practicality testing. The research data consisted of qualitative and quantitative data. Qualitative data were in the form of suggestions, criticisms, and comments from expert validators, while quantitative data were obtained from the results of instrument validity tests and empirical tests of relative permeability measurements of materials using the developed tool. Qualitative data were analyzed descriptively, while quantitative data were analyzed by comparing the results of tool measurements with reference standards or measurement results from comparison instruments with relative permeability standards of materials as can be seen in Table 1.

Table 1. Relative Permeability Standards of Materials

Material	Relative Permeability Range (μ_r)	Description/Condition	Source
Pure iron (annealed Fe, 99.95%)	Up to ~200.000	Ferromagnetic is very strong; the value depends on the annealing process and the magnetic field.	(Honarpour & Mahmood, 1988)
Steel (silicon steel / electrical steel)	4.000–38.000	Ferromagnetic; used in transformers and electric motors.	(Honarpour & Mahmood, 1988)
Ferritic/martensitic stainless steel	50–1.000	Intermediate ferromagnetic; values measured with FEM + Hall sensor at room and low temperature conditions.	(Denk & Hofbauer, 2023)
Austenitic stainless steel (304.316)	1.003–1.005	Paramagnetic (practically non-magnetic); not significantly affected by magnetic fields.	(Oxley et al., 2009)
Brass	~1	Non-ferromagnetic (hardly affected by magnetic fields).	(Honarpour & Mahmood, 1988)

Qualitative descriptive data analysis was used to process qualitative data in the form of suggestions, criticisms, and comments from the validator. The analysis was carried out by grouping and describing the qualitative information obtained from the expert validation sheet. Quantitative descriptive analysis was used to process the expert validation results in the form of questionnaire scores (Prasetiyo & Perwiraningtyas, 2017). Data was obtained through questionnaires filled out by material experts and media expert validators. In this study, three lecturers from Physics Education, FKIP, the University of Riau acted as expert validators. The analysis stage was carried out by determining categories and scores for the validation instrument answers filled out by the validator using a Likert scale, as shown in Table 2.

Table 2. Likert Scale Categories (Prasetiyo et al., 2017)

Score	Category
4	Very good
3	Good
2	Bad
1	Very bad

An assessment item is declared valid if all experts give a minimum score of 3. If the items on the questionnaire get a score of 1 and 2, they must be validated again until the items get a score of 3 or 4. Next, find the overall average of the instrument assessment sheet by comparing the number of scores obtained with the number of aspects assessed. Determination of the eligibility or validity criteria of a learning media is obtained by matching the total average with the validity category as shown in Table 2.

Table 3. Validity Categories (Prasetiyo et al., 2017)

Validity Index	Category
$3.50 \le x \le 4.00$	Very high
$3.00 \le x \le 3.50$	High
$2.00 \le x \le 3.00$	Low
$1.00 \le x \le 2.00$	Very low

An assessment item is declared valid if all experts give a minimum score of 3. Meanwhile, learning media are declared valid if all items have been declared valid by all validators or have validity index of at least 3.00. The validity index and validity categories can be seen in Table 3.

Table 4. Likert Scale Categories (Nisa et al., 2023)

Score	Category
4	Very Practical
3	Practical
2	Impractical
1	Very Impractical

Qualitative descriptive analysis was also used to process practicality data obtained from the field trial questionnaire. The instrument was administered to 29 students and two teachers to assess the ease, clarity, and attractiveness of the learning media. The assessment scores were rated using a Likert scale with categories as shown in Table 4.

The teachers' practicality results were analyzed by calculating the average for each statement. These averages were then matched against the practicality assessment categories, as shown in Table 5.

Table 5. Practicality Categories (Nisa et al., 2023)

Validity Index	Category
$3.50 \le x \le 4.00$	Very Practical
$3.00 \le x \le 3.50$	Practical
$2.00 \le x \le 3.00$	Less practical
$1.00 \le x \le 2.00$	Impractical

An assessment item is declared practical if all teacher respondents give a minimum score of 3. Meanwhile, learning media are declared practical if all items have been declared practical by all respondents or have a practicality index is at least 3.00. The practicality index and practicality categories can be seen in Table 5.

This method aligns with research by Ernidawati et al. (2025) who developed and tested the effectiveness of a metal permeability experiment tool on high school students' learning motivation. These results serve as an important reference indicating that R&D-based experimental media development should not only focus on product aspects but also go through an empirical validation process to ensure its usefulness in real-life learning (Ernidawati et al., 2025; Ansori et al., 2023).

By using this method, it is hoped that the development of a measuring tool for the relative permeability of materials can produce products that are valid, practical to use, and accurate in measuring relative permeability parameters, thereby supporting the learning process and basic research.

Results and Discussion

Analysis Stage

The process of developing and validating an experimental tool for the relative permeability of metal materials as a medium for learning high school physics is a research activity that emphasizes the integration of theoretical, practical, and pedagogical aspects to create an innovative product that can improve learning effectiveness. This development is carried out through a Research and Development (R&D) approach that aims to produce a product in the form of an experimental tool that is not only technically functional but also meets the needs of physics learning at the high school level. The initial stage in the development process is a needs analysis, in which researchers conduct direct observations in schools to determine the actual conditions of physics learning, especially in magnetism materials. The results of the observations generally indicate that most schools still experience limitations in laboratory facilities and experimental tools, so that learning tends to be theoretical. Teachers usually only rely on verbal explanations or illustrations from textbooks, while students do not have the opportunity to experience the experimental process themselves. This condition reinforces the urgency of developing a simple, affordable, and curriculum-relevant experimental tool (Hussain et al., 2021).

Product Design Stage

The second stage is product design. In this stage, researchers formulate the concept of an experimental tool capable of demonstrating the differences in relative permeability of various types of metals, such as iron, steel, copper, aluminum, and brass. The basic principle of this tool is to place a metal sample in a magnetic field generated by a coil, then observe its magnetic response using a sensor or a simple measuring instrument, such as a gaussmeter or magnetic needle. The tool was designed with attention to safety, practicality, and suitability for the abilities of high school students. The physical form of the tool was made simple for ease of use, while the procedure for using it was arranged step by step so that it could be understood by students who were new to the concept of relative permeability. The design of the relative permeability tool for metal materials can be seen in Figure 1.

The design also considers the visualization aspect, in which the tool must be able to clearly show the differences in magnetic reactions of metals so that students can make direct observations (Delpisheh et al., 2024). The relative permeability measuring tool is designed to consist of two main parts, namely the power supply and a circuit for reading current, voltage, magnetic field strength, and the relative permeability of the material.

A variable power supply is designed to convert AC voltage from a transformer into a stable and adjustable DC voltage as needed. This circuit consists of a step-down transformer, bridge diode, filter capacitor, LM317 regulator IC, resistor, and potentiometer. A circuit that reads current, voltage, magnetic field strength, and relative permeability of materials is designed to read and display the amount of electricity generated by solar panels. This circuit consists of an Arduino Uno as the main microcontroller, an INA219 sensor, an I²C-based 16x4 LCD module, push buttons as additional inputs, and a breadboard for connecting components.

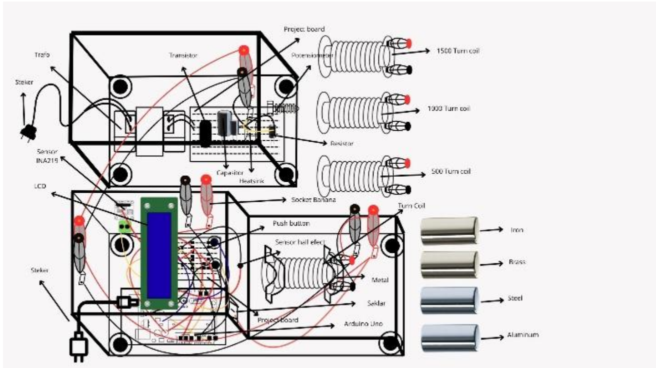

Figure 1. Design of relative permeability tool for metal materials

Each electronic component used in this system has a specific pin configuration that serves both a communication path and a power supply. The Arduino Uno, as the main microcontroller, is equipped with digital pins, analog pins, serial communication pins, and a power supply pin that can be used to connect various external modules. The pin configuration can be seen in Table 6.

Table 6. Arduino Uno Pin Configuration

PIN Number	PIN Name	Function
0	RX (Digital 0)	Serial data receiver
1	TX (Digital 1)	Serial data sender
2–7	Digital I/O	Digital input/output, some support PWM
8–13	Digital I/O	Digital input/output (pins 10–11–12–13 support SPI)
A0–A5	Analog Input 0–5	Reading analog signals (10-bit ADC)
A4	SDA	I²C communication line (data)
A5	SCL	I²C communication line (clock)
5V	VCC	+5 V power supply for external modules
3.3V	VCC	+3.3 V power supply for external modules
GND	Ground	System ground line
Vin	Voltage In	External voltage input (7–12 V)
RESET	Reset	Resetting the Arduino system

The INA219 sensor is a current and voltage sensor module based on the Texas Instruments INA219 chip that can measure current, voltage, and electrical power with high accuracy. This sensor uses I²C communication so it only requires two data pins (SDA and SCL) to connect to the microcontroller. In addition, the INA219 is equipped with current input terminals (IN+ and IN–) that are used as current measurement paths through the load. The pin configuration can be seen in Table 7.

Table 7. INA219 Sensor Pin Configuration

PIN Number	PIN Name	Function
1	VCC	+5 V power supply from Arduino
2	GND	Ground system
3	SDA	I²C communication data line
4	SCL	I²C communication clock line
5	IN+	Positive current input (from power source/supply)
6	IN−	Negative current input (out towards the load)

The Hall Effect sensor is a Hall effect-based sensor used to detect the presence of magnetic fields. This sensor produces an output voltage proportional to the intensity of the surrounding magnetic field. In this system, the Hall Effect sensor measures the magnitude of the magnetic field generated by the current flow in the coil. This sensor has three main pins: the power supply (VCC), ground (GND), and output (OUT). The pin configuration can be seen in Table 8.

Table 8. Hall Effect Sensor Pin Configuration

PIN Number	PIN Name	Function
1	VCC	+5 V power supply from Arduino
2	GND	Ground system
3	OUT	Produces an output voltage proportional to the detected magnetic field

The 16x4 LCD is a character display module capable of displaying up to 16 characters per line across 4 rows. This module generally uses the HD44780 driver and is equipped with an I²C (PCF8574) backpack, requiring only four main pins to communicate with the microcontroller. With I²C, the number of pins used is fewer than in parallel mode, making integration with the Arduino easier. The pin configuration can be seen in Table 9.

Table 9. 16x4 LCD Pin Configuration

PIN Number	PIN Name	Function
1	GND	Ground system
2	VCC	+5 V power supply from Arduino
3	SDA	I²C communication data line
4	SCL	I²C communication clock line

The relative permeability measuring instrument circuit is designed to be simple yet functional to accurately read current, voltage, and magnetic field values. This design allows the instrument to present real-time relative permeability data for materials, providing practicality and ease of use. Its main advantages are measurement efficiency, accuracy, ease of calibration, and relatively low design costs. This product is not only useful in material physics research and practical work, but can also be used as a contextual learning medium that integrates electromagnetic concepts, electronic instrumentation, and the application of microcontroller-based technology.

Product Development Stage

The third stage is prototyping. At this stage, the design is then translated into a concrete form. This development stage involves product creation, which involves two main stages:

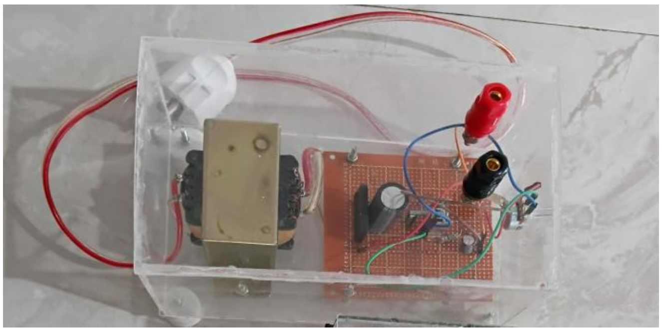

Figure 2. Power supply of relative permeability of material tool

The first step is to create a power supply. The process begins with preparing a 3A transformer. On the primary side, the transformer's 0V and 220V cables are connected to the power plug. Then, on the secondary side, the CT and 12V lines are connected to a bridge diode to convert AC voltage to DC. The positive and negative outputs of the bridge diode are connected to a 10000 μF electrolytic capacitor as a voltage filter for greater stability. Next, the positive leg of the capacitor is connected to the input of the LM317 IC. The output and adjust pins on the LM317 IC are connected through a 220 Ω resistor, while the IC input pin is connected to the positive leg of the 1000 μF capacitor. All negative legs of the capacitor are connected to the ground line. The potentiometer is installed with the ground leg to the GND line, the input leg to the 1000 μF capacitor, and the output leg to the resistor connecting the output-adjust pin of the LM317 IC. The output of the power supply is connected to the red banana socket (out +) and the black banana socket (out -) so that it can be used as a variable DC voltage source. The image can be seen in Figure 2.

The second stage is the creation of a circuit for reading the relative permeability of materials. The circuit begins with the installation of two banana sockets (red and black) as input terminals from the power supply. The red banana socket is connected to the IN+ pin of the INA219 sensor, while the black banana socket is connected to the Arduino ground line. The Arduino 5V pin is connected to the VCC of the INA219 sensor and the LCD, while the Arduino GND pin is connected to the GND of both. The I²C communication line is connected by connecting the Arduino A4 and A5 pins to the SDA and SCL pins of the INA219 sensor and the LCD IN– pin on the INA219 is connected to one of the switch legs. From this switch, two additional paths are created to two new banana sockets, which will later be used for mounting the test material samples. Two push buttons are installed with one leg connected to GND and the other leg to the Arduino D2 and D3 pins as control buttons, respectively. The Hall Effect sensor is installed with the configuration: VCC pin to 5V Arduino, GND pin to GND Arduino, and OUT pin to A0 Arduino pin. With this configuration, the Arduino is programmed to read current and voltage through INA219, detect the magnitude of the magnetic field through the Hall Effect sensor, and calculate the relative permeability value of the material. All measurement data is displayed in real-time on a 16×4 LCD. The process of this circuit is shown in Figure 3.

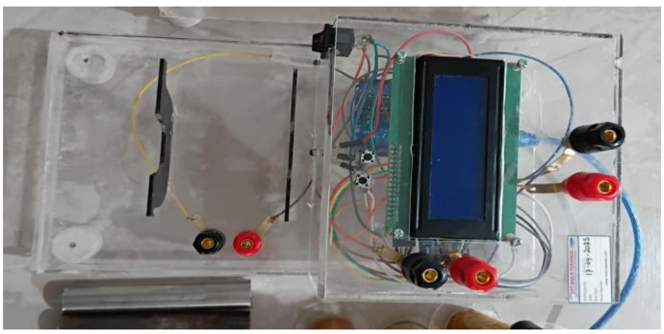

Figure 3. Relative permeability of materials reader circuit

The power supply circuit and the reader circuit have been completed, the coil is placed on the front of the reader circuit on the black board. This coil serves as a test bed for metal material samples for measuring relative permeability. The electrical connection is made by connecting the positive end of the coil to the positive terminal of the current source using a jumper, while the negative end of the coil is connected to the negative terminal using a jumper. In addition, the positive output of the power supply is connected to the positive input of the reader circuit using a jumper, while the negative output of the power supply using a jumper is connected to the negative input of the reader circuit using a jumper. With this configuration, the current from the power supply is flowed to the coil, then forwarded to the reader circuit to measure the current, voltage, and the magnitude of the magnetic field produced.

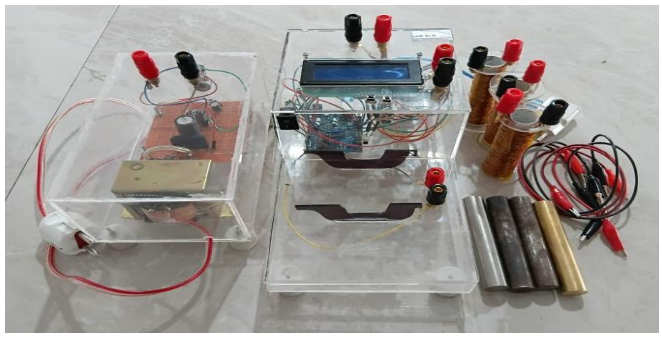

Figure 4. Relative permeability tool of material

Data Analysis of Empirical Test Results

An empirical test of the relative permeability of a material is conducted by comparing the measurement results using a developed tool with standard values. Relative permeability (μ_r) is the ratio of the permeability of a material to the permeability of a vacuum, which indicates the material's ability to conduct magnetic lines of force.

Table 10. Empirical Test Results of the Relative Permeability Tool for Metal Materials on a Coil with 500 Turns

Materials	N (Turns)	V (V)	I (mA)	B (mT)	μr
Iron	500	3	238	1.9	1.1
Iron	500	6	475	4	1.3
Iron	500	9	732	11.3	1.5
Steel	500	3	251	6.5	4.1
Steel	500	6	517	12.8	3.9
Steel	500	9	774	19	3.9
Brass	500	3	230	0.3	0.2
Brass	500	6	503	0.1	0.1
Brass	500	9	733	0.6	0.1
Aluminum	500	3	134	1	1.2
Aluminum	500	6	276	1.7	1
Aluminum	500	9	406	2.4	0.9

In materials science, the standard relative permeability value of each material varies greatly, influenced by crystal structure, purity level, heat treatment, and magnetic field conditions. This test is basically an evaluation of the precision and accuracy of the measurement results of the instrument against a reference standard. The data obtained are compared with the standard relative permeability values in the empirical test results of the relative permeability measuring instrument, which are divided into several tables according to the coil. The measurement results obtained using a coil with 500 turns can be seen in Table 10.

Tests were conducted using coils with the same number of turns, namely 500, and varying voltages on four materials: iron, steel, brass, and aluminum. The results showed that iron and steel had the highest relative permeability values, indicating strong ferromagnetic properties.

Meanwhile, aluminum and brass exhibited permeability values close to one, indicating weak paramagnetism and non-ferromagnetism. Increasing the voltage causes an increase in current and magnetic field in ferromagnetic materials, while in non-ferromagnetic materials the effect is not significant. Measurement results on a coil with 1000 turns can be seen in Table 11.

Table 11. Empirical Test Results of the Relative Permeability Tool for Metal Materials on a Coil with 1000 Turns

Materials	N (Turns)	V (V)	I (mA)	B (mT)	μr
Iron	1000	3	132	6.2	1.2
Iron	1000	6	260	10.3	1.6
Iron	1000	9	382	14.6	1.5
Steel	1000	3	106	9.1	3.7
Steel	1000	6	241	2.8	3.9
Steel	1000	9	371	2	3.8
Brass	1000	3	185	1.2	0.3
Brass	1000	6	287	1.6	0.4
Brass	1000	9	400	2.6	0.2
Aluminum	1000	3	83	0.1	0.9
Aluminum	1000	6	187	0.8	1.1
Aluminum	1000	9	254	0.5	1.3

Tests using a 1,000-turn coil were conducted on four materials: iron, steel, brass, and aluminum. Variations in voltage were applied to observe changes in current, magnetic field, and relative permeability for each material. The results showed that iron and steel exhibit distinct ferromagnetic properties, with higher relative permeability values than the other materials.

In iron, increasing the voltage results in an increase in the magnetic field, although the permeability tends to decrease, which may be due to the field saturation effect. Steel also shows a similar trend, but with a slightly higher initial permeability. Brass and aluminum exhibit very low magnetic field and permeability values, indicating that they are non-ferromagnetic. Aluminum is weakly paramagnetic, while brass has almost no response to a magnetic field. The results of measurements on a coil with 1500 turns can be seen in Table 12.

Tests using a coil of fifteen hundred turns were conducted on four materials: iron, steel, brass, and aluminum. Variations in voltage were applied to observe changes in current, magnetic field, and relative permeability in each material. The results showed that iron and steel exhibit stronger ferromagnetic properties than the other materials.

Table 12. Empirical Test Results of the Relative Permeability Tool for Metal Materials on a Coil with 1500 Turns

Materials	N (Turns)	V (V)	I (mA)	B (mT)	Mr
Iron	1500	3	86	14.2	1.8
Iron	1500	6	189	10.1	1.1
Iron	1500	9	258	6.2	1.5
Steel	1500	3	91	4.8	3.8
Steel	1500	6	171	9.7	3.9
Steel	1500	9	352	14.6	4.1
Brass	1500	3	88	0.4	0.3
Brass	1500	6	195	0.6	0.2
Brass	1500	9	270	1.3	0.3
Aluminum	1500	3	95	1.9	1
Aluminum	1500	6	182	1.2	1.3
Aluminum	1500	9	279	0.5	1.1

In iron, the magnetic field value tends to decrease with increasing voltage, while the relative permeability remains stable. This indicates that iron is able to conduct the magnetic field efficiently despite changes in current. Steel shows a relatively high permeability value at low voltages, but decreases with increasing voltage, indicating a possible magnetic field saturation effect. Brass and aluminum have very low magnetic field and permeability values, indicating non-ferromagnetic properties. Aluminum still exhibits a slight response to the magnetic field due to its paramagnetic nature, while brass shows almost no significant change.

From the results of the comprehensive empirical tests, it can be observed that iron has an average relative permeability (μr) value of 1.44, which indicates strong ferromagnetic properties, while steel has an average μr of 3.89, the highest among all tested metals, indicating very strong ferromagnetic properties. Brass has an average μr of 0.23, which indicates non-ferromagnetic properties, while aluminum has an average μr of 1.09, which is weakly paramagnetic. Overall, steel and iron are able to strengthen magnetic fields effectively, while brass and aluminum are almost unaffected by magnetic fields.

The results of tests with varying numbers of turns showed that the more turns present in the coil, the greater the magnetic field formed, especially in ferromagnetic materials. Iron and steel showed a strong response to changes in electric current, while aluminum and brass showed almost no significant change. The relative permeability values in iron and steel were higher than those in aluminum and brass, indicating a better ability to strengthen the magnetic field. At high voltages, the decrease in permeability values in iron and steel is likely caused by magnetic field saturation. In general, it can be concluded that the number of turns affects the magnetic field strength in ferromagnetic materials, but has no significant effect on non-ferromagnetic materials.

Validation Results of Relative Permeability Tool of Materials

To strengthen the empirical test results, ferrite content testing was also conducted using a Fischer Feritscope DMP30 at PT DETECH Material Testing Laboratory. Testing was conducted on 10 cm long samples and measured at three test points for four materials: steel, iron, aluminum, and brass.

The test results show that steel has an average ferrite content of 90.5%, indicating that this material is dominated by the ferrite phase and has very strong ferromagnetic properties. Iron has an average ferrite content of 65.7%, also considered high and shows strong ferromagnetic characteristics although lower than steel. In contrast, aluminum has an average ferrite content of only 0.76%, indicating a very small or almost undetectable amount of ferrite, while brass shows no readings, meaning it does not have a significant ferrite content. The ferrite test results can be seen in Table 13.

Table 13. Results of Ferrite Content Testing of Four Types of Materials (Detech, 2025)

Materials	Sample Marking	Location	Point 1 (%)	Point 2 (%)	Point 3 (%)	Average (%)	Description
Steel	MHS.9.2	Base Metal	91.30	91.20	89.00	90.50	Medium ferrite, according to the characteristics of ferritic steel
Iron	MHS.9.2	Base Metal	67.30	55.60	74.20	65.70	Ferrite dominant or high
Aluminum	MHS.9.1	Base Metal	0.74	0.83	0.70	0.76	Very low ferrite, almost undetectable
Brass	MHS.9.2	Base Metal	–	–	–	–	Not detected (the device does not provide a reading)

These findings from PT DETECH reinforce the empirical results of relative permeability testing, which show that iron and steel are predominantly ferromagnetic due to their high ferrite content, while aluminum and brass are non-ferromagnetic due to their lack of significant ferrite content. Thus, these external laboratory results demonstrate the accuracy and validity of the relative permeability tool in identifying the magnetic characteristics of various metal materials.

The testing was also strengthened by the results of the instrument calibration conducted by PT. Multi Teraindo (certificate number: S.25.015211, dated September 17, 2025). This calibration ensures that the instrument complies with international measurement standards and has an acceptable level of uncertainty. Thus, the measurement results from the experimental instrument are more guaranteed to be accurate and can be scientifically accounted for. Calibration results can be seen in Table 14 for voltage and Table 15 for current.

Table 14. DC/AC Voltage Calibration Results (PT. Multi Teraindo, 2025)

N (Turns)	Tool Designation (V)	Correction (V)	Standard Designation (V)	Uncertainty (V)
	2.5	0.00	2.50	0.03
500	7.5	0.00	7.50	0.03
	10.0	0.00	10.00	0.03
	2.5	0.00	2.50	0.03
1000	7.5	0.01	7.51	0.03
	10.0	-0.01	9.99	0.03
	2.5	0.00	2.50	0.03
1500	7.5	0.00	7.50	0.03
	10.0	-0.01	9.99	0.03

Table 15. DC/AC Current Calibration Results (PT. Multi Teraindo, 2025)

N (Turns)	Voltage (V)	Tool Designation (mA)	Correction (mA)	Standard Designation (mA)	Uncertainty (mA)
	2.5	158.0	4.2	162.2	0.06
500	7.5	495.0	4.9	499.9	0.06
	10.0	772.0	8.0	780.0	0.06
	2.5	77.0	1.0	78.0	0.06
1000	7.5	301.0	6.2	307.2	0.06
	10.0	403.0	5.3	408.3	0.06
	2.5	68.0	1.1	69.1	0.06
1500	7.5	204.0	3.2	207.2	0.06
	10.0	280.0	4.1	284.1	0.06

Validation was conducted by three experts with doctoral degrees in science education. Validation by material experts aimed to ensure that the experimental equipment complies with correct physical principles, particularly those related to the laws of magnetism and the concept of relative permeability. Media experts assessed the equipment's appearance, clarity of instructions, and compliance with pedagogical standards. Meanwhile, teachers, as practitioners, assessed its practicality for classroom use, safety, and usefulness in helping students understand the concept. The validation instrument consisted of an assessment sheet covering aspects of content feasibility, construction, presentation, and language. Validation results were analyzed quantitatively by calculating the average score, then categorized into very feasible, feasible, fairly feasible, or not feasible (Kamil et al., 2022). The validation results conducted by three validators are shown in Table 16.

Table 16. Validation Results of the Relative Permeability Tool for Metal Materials

Validator	Tool Functionality	Learning Elements	Convenience	Aesthetics and Construction	Job Security	Average
1	3.75	4	4	3.67	3.5	3.78
2	3.75	3.83	4	3.67	4	3.85
3	3.5	3.5	3.67	3.67	4	3.67
Average	3.67	3.78	3.89	3.67	3.83	3.77
Validation Category	Very High	Very High	Very High	Very High	Very High	Very High

Based on the validation results carried out by the validator on the learning media Experimental Tool for Testing the Relative Permeability of Metal Materials, the results obtained indicate that each aspect of the assessment showed a very high level of validity. In the aspect of tool function, the assessment results showed a very high category. This tool is considered to have functioned well in measuring the relative permeability values of various metal materials accurately. In addition, the tool is able to show differences in magnetic response in various types of metal and can be used to calculate physical quantities relevant to magnetism. The precision of the measurement results readings is also considered good, so the tool has fulfilled its main function as an accurate and reliable experimental medium. However, the validator provided a note that the accuracy of the tool results should continue to be monitored and calibrated periodically to maintain measurement accuracy.

In terms of learning elements, the validation results were in the very high category. This learning media is considered effective in applying magnetic concepts such as magnetic induction, magnetic fields, and permeability in physics learning activities at the high school level. This tool is also able to integrate physical phenomena with everyday life and can train students' scientific thinking skills. Thus, the tool is highly relevant for use in project-based and experimental learning because it helps students connect theory with practice and fosters curiosity about magnetic phenomena around them.

The ease of use aspect received a very high rating. This experimental tool is easy to set up before use, easy to operate, and easy to transport. Teachers and students can use it without special training. However, the validator recommended careful attention to the position and layout of the tool to minimize reading errors and ensure stability during the experiment.

In terms of aesthetics and construction, the validation results showed a very high rating. The experimental apparatus has an attractive shape, with a well-organized and proportional structure. The components are well-assembled and display a neatness that reflects a well-thought-out design. However, the validator recommended continued attention to the robustness of the apparatus and improvements to certain parts to ensure it is more durable for repeated use in learning.

The safety aspect of operation is categorized as very high. The experimental equipment is deemed safe for use in physics lessons, both in the classroom and in the laboratory. All electrical components and power connections are well protected and pose no risk to users. The validator only added a recommendation that the electrical system and protective casing of the equipment be continuously monitored to ensure user safety during measurements and observations.

Overall, the validation results indicate that the Metal Material Relative Permeability Testing Experimental Tool has a very high level of validity and is suitable for use as a physics learning tool. This tool not only supports students' understanding of the concepts of magnetism and permeability of metal materials, but also serves as an innovative tool for practicing scientific thinking skills, critical thinking, and improving the quality of experiment-based physics learning in schools.

This validation stage is crucial because it provides an objective overview of the product's strengths and weaknesses. For example, if the material expert finds that the device is unable to show a significant difference between ferromagnetic and non-ferromagnetic metals, the researcher needs to increase the device's sensitivity, for example by increasing the number of coil turns. If the media expert deems the display unattractive or the instructions for use too complicated, improvements to the visual design and manual development are necessary. This comprehensive validation ensures that the resulting product is not only scientifically sound but also appropriate for the characteristics of high school students.

Practical Results of the Relative Permeability of Materials Tool

The practicality of the seawater purifier was assessed by high school physics teachers using three main aspects: tool quality, learning, and usability and efficacy. The quality aspect focused on ease of use, attractiveness of design, and durability of construction during use in learning. The learning aspect focused on the tool's relevance to learning objectives, its ability to facilitate conceptual understanding, and its suitability for the material being taught. Meanwhile, the usability and efficacy aspect assessed the extent to which the tool was useful in supporting the learning process, encouraging student engagement, and delivering results consistent with the practicum objectives. The results of the teacher practicality test are shown in Table 17.

Table 17. Results of Teacher Practicals of Relative Permeability of Materials

Practicals	Practicality Point		
	Tool Quality Aspects	Learning Aspects	Benefits and Sustainability Aspects
1	4	4	4
2	3.8	3.6	4
3	4	4	4
4	3.6	3.8	3.6
5	4	4	4
6	3.2	3.6	4
7	4	4	4
8	4	4	4
9	4	4	4
10	3.8	4	3.8
11	4	4	4
12	4	3.8	3.6
13	4	4	4
14	3.4	3.8	3.6
15	3.8	5	3.4
16	3.8	3.8	5
Average	3.8375	3.9625	3.9375

Based on the results of the MGMP teacher satisfaction questionnaire on the learning media for the relative permeability of metal materials, the results showed that each aspect of the assessment showed a high level of satisfaction to very practical. In terms of tool quality, teachers assessed that this tool has a simple and easy-to-use display, with components arranged neatly and safely when operated. The measurement results in the form of voltage (V), current (I), magnetic field (B), and relative permeability (μr) can be displayed clearly via the LCD screen, making it easier for users to read the experimental data. In addition, the tool can be used repeatedly without experiencing significant damage. This shows that functionally, the tool has met the requirements as a practical and durable learning medium, although improvements are still needed in the cable arrangement and sensor calibration to increase the accuracy of the measurement results.

In the learning aspect, the questionnaire results showed a very practical category. Teachers stated that this tool helps in explaining the concept of magnetic permeability in a concrete and interesting way. Students become more enthusiastic in participating in learning because they can see directly how the magnetic properties of various metal materials are tested and compared. In addition, this tool supports the achievement of physics learning objectives because it integrates electromagnetic theory with real-world practice. The time spent using the tool is also in accordance with the duration of class learning, so its use is efficient without disrupting the time allocated for discussion activities or drawing conclusions. This tool is considered relevant to the high school/vocational school physics curriculum, especially on the material on the magnetic properties of materials, so it has great potential for widespread use in school practical activities.

The benefits and sustainability aspects also earned the category of Very Practical. Teachers felt that this tool was able to increase their creativity in teaching because it provided a more interactive and experiment-based learning alternative. In addition, this tool supports project-based practicum activities (project-based learning) that can encourage students to engage in scientific exploration. The tool was also considered an innovative medium in MGMP activities because it was able to enrich teachers' experiences in developing simple yet meaningful tool-based learning. Furthermore, this tool provides contextual learning experiences for students through direct observation of magnetic phenomena, thus strengthening conceptual understanding. Teachers also assessed this tool has potential for further development, both in the form of improving digital features and adding automatic sensors to increase accuracy and efficiency.

Overall, the questionnaire results indicate that the relative permeability of metals tool has a very high level of practicality and acceptability. This tool is not only effective in supporting students' understanding of the concept of magnetism, but also plays a role in increasing teacher creativity and enriching physics laboratory-based learning activities. Thus, this tool is worthy of widespread use as an innovative learning medium to support the implementation of a modern physics curriculum that emphasizes scientific thinking skills and project-based learning.

Thus, the development and validation process for the relative permeability of metal materials experimental tool includes a series of structured stages: needs analysis, design, prototyping, empirical testing, expert validation, and practicality testing. This process is cyclical, meaning that researchers can return to previous stages if deficiencies are found. Each stage plays a crucial role in ensuring that the final product is truly feasible, scientifically, pedagogically, and practically. Ultimately, the resulting product is expected to provide a solution to the limitations of learning media in schools, clarify abstract physics concepts, and improve the quality of science education in Indonesia.

Overall, the development and validation process for the relative permeability experimental tool for metals is a series of structured and systematic steps. This process ensures that the resulting product not only complies with scientific principles but is also pedagogically and practically suitable for use. With this experimental tool, students can learn physics more meaningfully because they can directly observe phenomena that were previously only explained theoretically. This not only improves conceptual understanding but also fosters students' learning motivation and scientific skills, such as observation, data analysis, and drawing conclusions. Ultimately, the development and validation of this tool is expected to be one of the solutions to improve the quality of physics learning in Indonesia, particularly in the abstract topic of magnetism, while also making a real contribution to producing a younger generation that is more scientifically literate and ready to face the challenges of the 21st century.

Conclusion

Based on the entire process that has been carried out, it can be concluded that the development and validation of the relative permeability experimental tool for metal materials were conducted systematically and in a structured manner, including the stages of needs analysis, design, prototype creation, empirical testing, expert validation, and practicality assessment by high school physics teachers. The developed tool has proven to be feasible from scientific, pedagogical, and practical perspectives. The results of the empirical test show that the tool is able to distinguish between ferromagnetic and non-ferromagnetic properties in various types of metals, while the results of expert validation and calibration confirm its accuracy, safety, and feasibility for use. The practicality assessment by teachers shows that the tool is easy to use, interesting, supports the achievement of learning objectives, and provides real benefits for the learning process. Overall, this experimental tool not only clarifies abstract concepts in magnetism but also encourages students' scientific skills, such as observation, analysis, and drawing conclusions, thereby making it an effective solution to improve the quality of physics learning in schools.

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Author contributions

All author in this research has significant roles.

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Conflicts of Interest

All author declares that there is no conflict of interest.

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