INSECTA Vol. 6 No. 1, 2025, pp. 51 - 63

Available online at
INSECTA
Integrative Science Education and Teaching Activity Journal
Journal homepage : https://jurnal.iainponorogo.ac.id/index.php/insecta

Article

Optimizing Boyle's Law Practicum Using a PhET-Based Virtual HOT Lab

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Article Info
Article history:
Received: March 14, 2025
Accepted: April 21, 2025
Published: May 31, 2025

Keywords:

Boyle's Law;
HOT Lab;
PhET simulation;
Pressure-volume relationship;
Virtual laboratory

ABSTRACT
This research emphasizes the urgency of using PhET-based virtual laboratories in Boyle’s Law experiments to enhance students’ understanding of gas properties, specifically the relationship between pressure and volume at constant temperature. By applying an inquiry-based HOT Lab approach, students can actively manipulate gas variables and observe real-time pressure changes through the simulation. The findings indicate that the PhET simulation significantly aids students in grasping Boyle’s Law principles by providing an interactive and engaging learning experience. Furthermore, this approach supports the development of critical and analytical thinking skills and accommodates various learning styles and paces, making it an inclusive educational tool. Given the challenges in physics learning, especially in the context of online education, integrating virtual simulations with physical laboratory activities in the future could enrich the learning experience and deepen students’ understanding of fundamental physics concepts.

INTRODUCTION

Capabilities such as critical thinking, problem-solving, and teamwork are essential 21st-century skills that are significantly influenced by laboratory activities in science education (Maghribi, 2023; Miaturrohmah & Fadly, 2020). Students not only learn the fundamentals of science through practical activities but also have the opportunity to apply these concepts to real-world situations (Qolbyatin et al., 2023). Students have the opportunity to practice practical skills that are essential in today's era of globalization and technological advancement (Zayas & Rofi’ah, 2022). Critical thinking and adaptability are essential (Malik et al., 2022). Research has shown that taking part in laboratory experiments can improve students' understanding of science concepts and build the analytical abilities needed to deal with complex problems in everyday life (David et al., 2022). In other words, laboratories help students become experts and ready to face a changing world by combining theory with practice. However, practical activities in laboratories often face several challenges, such as a limited number of tools, high costs, and limited time. This is especially true when learning has to be done online (Febriansyah et al., 2021). Under these circumstances, simple technologies such as smartphones have been widely used by students and the general public to obtain information quickly and thoroughly (Mulyani & Arif, 2021). Research conducted by (Rembulan & Susanti, 2021) shows that students prefer virtual laboratories over real laboratories due to higher time efficiency, allowing experiments to be conducted anywhere and anytime without having to physically go to the laboratory(Kuncorowati et al., 2021).

Often, physics learners, especially those dealing with abstract concepts such as Boyle's Law, face difficulties in reconciling the difference between theory and its application in the real world. Because these concepts are abstract and processes are not immediately apparent, many students struggle to understand how these concepts apply in real life (Fitriah & Irawan, 2021). HOT Lab Practicum is an innovative approach to science learning that combines hands-on experimentation with real-time digital data analysis. This allows students to be more active and engaged in understanding the scientific process thoroughly (Rosalina & Suhardi, 2020). According to research conducted by Adam Malik and his team (Malik et al., 2018), Students have the opportunity to apply physics ideas to real-world situations through practical activities in the HOT Lab. They also learn how to present experimental results in front of the class, invite discussions, and cooperate with the teacher and other groups (Dwi et al., 2024). The ability to think critically and communicate scientifically, which are important skills in the 21st century, is strengthened by this (Lestari & Hadi, 2022). Identifying opportunities, seeking information, framing problems, creating ideas, developing solutions, testing hypotheses, conducting labs, and finally evaluating and communicating the results of the HOT Lab model. Each of these steps helps students learn systematically about the scientific process, giving them the opportunity to think creatively, analyze data, and connect experimental results to theory. (Malik & Setiawan, 2016). This approach allows students to develop deep analytical and synthesis skills, as well as the ability to apply physics knowledge to more contextual situations, helping to bridge the gap between theory and practice(Novita Oktaviani & Ulinnuha Nur Faizah, 2024).

Innovative approaches such as Boyle's Law that can help students understand basic concepts that are often complex are necessary to achieve effective science education (Rizkia et al., 2021). Boyle's Law is a fundamental principle in physics and chemistry that explains the inverse relationship between the pressure and volume of a gas at a constant temperature. Robert Boyle's experiments in 1662 revealed that when the pressure on a gas increases, its volume decreases proportionally, and vice versa (Lilik, 2023). This relationship is visually represented by an isothermal curve, which is hyperbolic in shape and illustrates how gas temperature remains constant while pressure and volume vary (Giancoli, 2001). The real-world relevance of Boyle's Law is evident across various technological and medical applications. It plays a critical role in the design and operation of mechanical systems that rely on pressure regulation, such as hydraulic machinery and laboratory instruments. Additionally, Boyle's Law is essential in the medical field, particularly in controlling anesthetic gas dosages and managing respiratory ventilation systems, where precise pressure-volume relationships are crucial for patient safety. Understanding these applications highlights the urgency of effectively teaching Boyle's Law to prepare students for challenges in science and technology(Awalin & Ismono, 2021). By integrating students' theoretical knowledge of Boyle's Law with its practical applications, educators can help learners better connect abstract scientific concepts to tangible phenomena (Malik et al., 2022). This educational approach not only deepens conceptual understanding but also equips students with the skills needed to innovate and solve real-world problems in a rapidly evolving scientific landscape (Yasir & Dwiyanti, 2024).

Although Boyle's Law is essential to understanding the concept of gases and how it can be used in everyday life, students often struggle to understand how this law is applied in real life. PhET simulations, a project at the University of Colorado Boulder, offers a range of interactive simulations that support learning in physics, chemistry, biology, math and more. Using educational technology like this can offer a more interactive and engaging learning experience that bridges theory with hands-on experience. (Masruroh et al., 2021). This simulation gives students the opportunity to conduct virtual experiments with important concepts, such as testing the relationship between pressure and volume in a gas, which is the basis of Boyle's Law. They also have the opportunity to change various parameters, including pressure and volume, and see the changes that occur. They can also test hypotheses in a safe and controlled virtual environment, which is definitely more accessible than a physical laboratory (Rembulan & Susanti, 2021). Students can engage directly in the learning process with this interactive feature. Ultimately, this will help them understand science concepts more deeply and contextually (Sumantri & Wibowo, 2023). To overcome the limitations of physical facilities in school or university laboratories, PhET (Physics Education Technology) simulations are a very potential solution. Students can perform various experiments anywhere without the need to use physical laboratory tools, which are sometimes limited in number or difficult to access, especially in cases where the practice has to be done online(Syauqi et al., 2024). PhET simulations allow students to learn and understand physics concepts, including the gas concept in Boyle's Law, in an interactive virtual environment without relying on a physical laboratory. This enhances learning autonomy and improves access to experiment-based learning (Pristianti & Prahani, 2023)

Several studies have demonstrated that PhET simulations are highly effective when integrated into the Higher Order Thinking (HOT) Lab method, particularly in enhancing students' skills and understanding of complex scientific concepts. One concept that often poses difficulties for students is Boyle's Law, which involves abstract thermodynamic principles and is challenging to visualize directly. Research, including a study by Venkatesh, S. (2025), indicates that Boyle's Law frequently presents challenges in student comprehension. A thorough understanding of this law is crucial due to its wide-ranging applications in fields such as mechanical engineering, chemistry, and medicine. According to Putra et al. (2021), the HOT Lab approach not only involves conducting physical experiments but also integrates digital tools like PhET that allow real-time data manipulation and visualization. Compared to other virtual labs that tend to follow linear, step-by-step instructions, PhET simulations offer greater flexibility, interactivity, and conceptual clarity by enabling students to freely adjust variables such as pressure and volume and immediately observe the dynamic changes through updated graphs and molecular models. Antonio & Prudente. (2023) note that this feature encourages students to engage in exploration and hypothesis testing, which are core elements of HOT-based learning. Moreover, Malik et al. (2023) emphasize that the integration of PhET into HOT Lab not only strengthens conceptual mastery but also fosters critical thinking, independence, and scientific reasoning, advantages that are less prominent in virtual labs with more rigid or demonstration-only formats.

This study aims to evaluate the effectiveness of using a PhET-based HOT Lab virtual laboratory to optimize learning in Boyle's Law experiments. By comparing students' understanding of Boyle's Law through virtual versus traditional lab methods, this research seeks to provide insights into the role of technology in physics education. Using the PhET-based HOT Lab method, the study focuses on enhancing students' comprehension, critical thinking, and creativity in a learning environment that encourages active participation. This innovation aims to bridge the gap between virtual and traditional labs, offering a promising solution for future science education.

METHODS

This study employs a quasi-experimental method utilizing a HOT Lab approach integrated with virtual simulations through the PhET platform. The subjects of the study consist of 11th-grade high school students engaged in physics education. The main objective is to measure students' understanding of Boyle's Law and the improvement of their analytical thinking skills through the Higher Order Thinking method. The learning process is designed by combining PhET simulations with a HOT Lab-based practicum module to encourage active student interaction and facilitate deeper conceptual understanding. The virtual lab steps include introducing the concept of Boyle's Law, interactive manipulation of pressure and volume variables within the simulation, real-time observation of results through dynamic graphs, and group discussions to evaluate and analyze the collected data, making the 5 not only observational but also reflective and critical (E. A. Putri & Fadly, 2022).

To make the research easier to understand, the research path is depicted in a flow chart. Figure 1 shows a structured series of experiments and data collection, which refers to methods that have been used in similar research by (Purnama et al., 2021), which supports the effectiveness of simulation as a learning tool. The first step is the preparation of the simulation, where the independent variables of gas pressure and volume are set at certain initial conditions. The next step is to measure the initial box length, which is set at 10 Nm using a virtual ruler. This measurement is done by clicking "width" on the simulator, where a ruler will appear at the bottom of the screen, then the researcher records the initial box length value. After determining the initial box length, experiments were conducted by varying the pressure and gas volume parameters. At this stage, the pressure indicated on the barometer was observed and recorded in the table. Further box size variations were made by changing the box length to 12 Nm, 13 Nm, 14 Nm, and 15 Nm, and then recording the results of the pressure read on the barometer for each box size. This process was repeated 10 times to obtain several pressure values at the manometer and box length, with data taken and recorded at each change of condition.

The interpretation of the experimental data combined both qualitative and quantitative approaches. Qualitative interpretation involved identifying patterns and relationships between pressure and volume according to Boyle's Law, while quantitative interpretation was based on direct observation of numerical data provided automatically by the PhET simulation (Justin & Abhiyoga, 2021). This automatic data capture ensured consistent and reliable results, allowing for clearer understanding by connecting experimental findings with theoretical concepts (Fadly, 2022). Gas pressure is measured as the independent variable with a virtual manometer, while volume is set as the dependent variable in the simulator. Figure 2 shows the circuit schematic used for virtual data capture. It provides a further overview of the procedure used in this experiment.

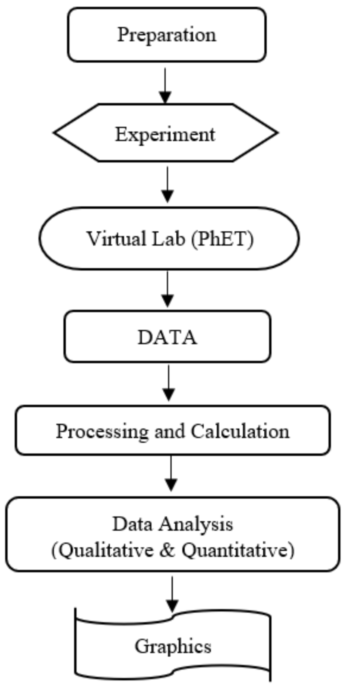

Figure 1. Research Flow
Source: Personal documentation

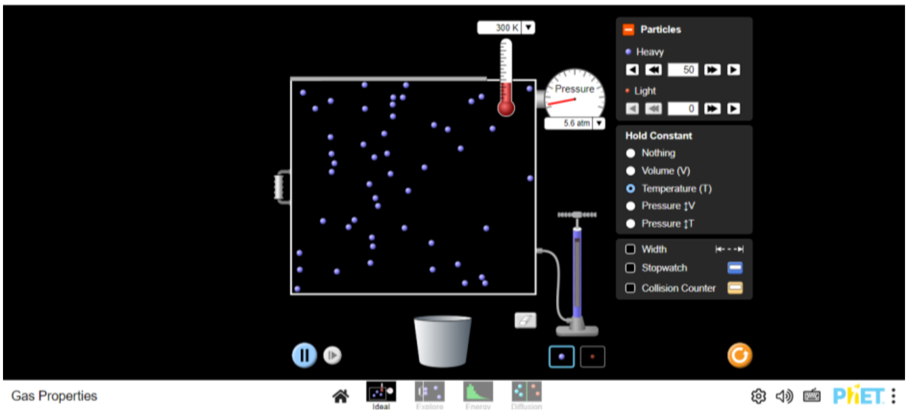

Figure 2. Schematic of The Virtual Experiment Circuit
Source: Personal documentation

The experiments were conducted in a virtual laboratory equipped with laptop devices and adequate internet access. The research location was not physically restricted as the entire experimental process took place in a digital simulation. Observation data from the simulation was collected and processed using methods that have been adopted from previous research, so that the validity and reliability of the data can be maintained (Widiyanti & Susilayati, 2023).

RESULTS AND DISCUSSION

This research was conducted with the aim of optimizing the Boyle's Law practicum using a PhET-based virtual laboratory. In this study, we analyzed the relationship between pressure and volume of a gas at a constant temperature of 300 K. Beyond verifying theoretical principles, this research also explores the practical implications of Boyle's Law in real-world contexts, such as medical devices using syringes or air pumps, and industrial applications involving gas compression, thereby enhancing the relevance of the study. The PhET simulation in this research mimics the working of a syringe or a gas pump, allowing users to compress or expand a virtual gas by adjusting a movable piston, similar to real-life medical and mechanical systems. Through the data obtained from the simulation, we conducted an in-depth analysis to understand how volume variation affects gas pressure.

For example, the following table shows a small sample of data generated from the simulation:

Table 1. Experiment Result Data

Gas Volume (m^3)	Pressure (atm)
1.5×10^{-24}	14,0
1.4×10^{-24}	15,0
1.3×10^{-24}	15,8
1.2×10^{-24}	21,2

Through this interaction, students can directly observe the inverse relationship between volume and pressure, reinforcing their understanding of the abstract concepts in Boyle's Law. The simulation automatically provides data that students analyze to validate their theoretical predictions. This interactive learning approach also enhances critical thinking and data interpretation skills, encouraging students to be more actively engaged and to better grasp scientific principles.

The data generated from the PhET simulation clearly illustrate the inverse relationship between gas volume and pressure at a constant temperature, consistent with Boyle's Law. For example, when the gas volume increases from approximately 1.2×10^{-24} m^3 to 1.5×10^{-24} m^3, the pressure correspondingly decreases from around 21.2 atm to 14.0 atm. This trend is consistently observed across multiple measurements, despite minor fluctuations typical of experimental data, which helps students appreciate the variability and accuracy of real-world scientific observations. By engaging with the simulation, students can visualize and analyze how changes in volume directly impact pressure, reinforcing the fundamental principle that their product remains constant under fixed temperature conditions. This interactive approach not only supports theoretical understanding but also fosters practical skills in data interpretation and critical thinking.

This experiment shows that the PhET simulation has helped students better understand the interaction between gas pressure and volume. The data collected supports the basic principle of Boyle's Law, which is that an increase in gas volume always results in a decrease in pressure at constant temperature. In addition, they allow students to see how these two variables affect each other in real time.(Rohana et al., 2022)

The calculation data obtained from the Boyle's Law experiment data are listed in the following table:

Table 2. Boyle's Law Experiment Calculation Results

No	Box length (Nm)	Volume (m^3)	Pressure (Pa)	P X V (Pa/m^3)
1	12	1,2 x 10^{-24}	2126460	2,552 x 10^{-18}
2	13	1,3 x 10^{-24}	1641083	2,131 x 10^{-18}
3	14	1,4 x 10^{-24}	1529900	2,142 x 10^{-18}
4	15	1,5 x 10^{-24}	1396467	2,095x 10^{-18}

Table 2 shows the results of calculations that illustrate the effect of volume changes on gas pressure. From the data listed, it can be seen that as the box length increases, the gas volume also increases, while the gas pressure shows a decrease.

In the first experiment with a box length of 12 Nm, the gas volume was 1.2 x 10^{-24} m³ and the measured pressure was 2,126,460 Pa. When the box length was increased to 13 Nm, the volume increased to 1.3 x 10^{-24} m³, and the pressure decreased to 1,641,083 Pa. This phenomenon is consistent with Boyle's law, which states that the pressure and volume of a gas are inversely related at constant temperature. This means that if one variable increases, the other variable will decrease, as long as the amount of gas and temperature remain constant. The product of pressure and volume (P × V) in each experiment shows relatively constant values, despite minor variations. For example, in the first experiment, the value of P × V was 2.552 x 10^{-18} Pa/m³, while in the second experiment it became 2.131 x 10^{-18} Pa/m³. This constant value of P × V reflects the basic principle of Boyle's law that for an ideal gas, the product of pressure and volume remains constant at a certain temperature.

The use of PhET-based virtual laboratories allows students to see the relationship between pressure and volume directly, thereby enhancing their conceptual understanding(Masruroh et al., 2021). This simulation not only reinforces theoretical aspects of Boyle's Law but also enables students to manipulate various variables and observe their effects in real time. Compared to traditional physical laboratories, virtual simulations have been shown to increase student engagement and conceptual mastery due to their and accessible nature (Munawaroh et al., 2022). Sundari et al., (2021) also found that students working with virtual labs demonstrated better performance and deeper inquiry-based learning compared to those using only physical tools. Therefore, the analysis of this study's data, showing that a decrease in pressure is negatively correlated with an increase in volume, strongly supports Boyle's Law. Overall, this research highlights how virtual laboratories can offer meaningful scientific experiences, enhancing students' understanding of gas properties and their real-world applications in physics.

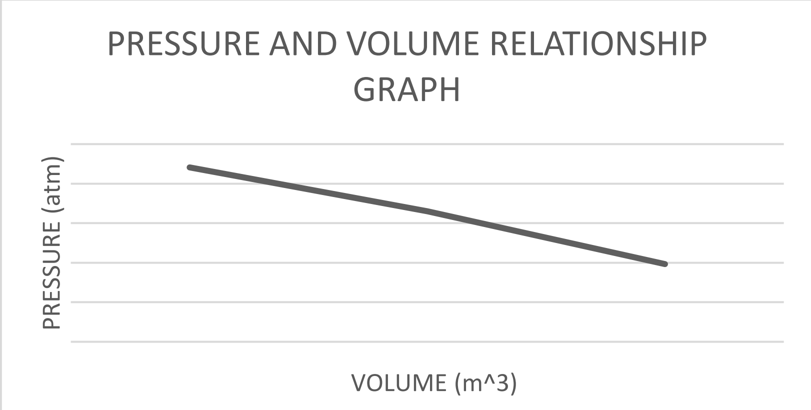

Figure 3. The Graph of The Relationship between Pressure and Volume

Figure 3 shows the graph of the relationship between pressure (P) and volume (V) of the gas at a constant temperature of 300 K, based on the calculations that have been performed. In this graph, the horizontal axis represents the volume of the gas, while the vertical axis represents the pressure of the gas

A clear and opposite relationship between pressure and volume is shown on the graph, which is in line with Boyle's law: as the volume of a gas increases, the pressure of the gas tends to decrease, and vice versa. This demonstrates the fundamental nature of gases, where the product of pressure and volume remains constant for a fixed amount of gas at a constant temperature (R. Weber et al., 2020). The graph shows a consistent downward trend indicates that as the volume increases, the gas pressure decreases. For example, at smaller volumes (e.g. 1.2 x 10^{-24} m^3), the pressure reaches 2,126,460 Pa, while at a larger volume (e.g. 1.5 x 10^{-24} m^3), the pressure decreases to 1,396,467 Pa.

As the pattern shows that the pressure of a gas is inversely proportional to its volume, it can be inferred that if students understand this graph, they will find it easier to use Boyle's law in a wider context, such as in industrial applications and scientific experiments. In addition, this graph provides a clear picture of how changes in volume affect pressure, which helps students better understand and internalize these ideas. (Sabila Fatkhi & Solihah, 2023). The use of PhET-based virtual laboratories allows students to conduct simulations and see the results directly, enhancing their engagement and understanding of these physical phenomena.(Yanti et al., 2023).

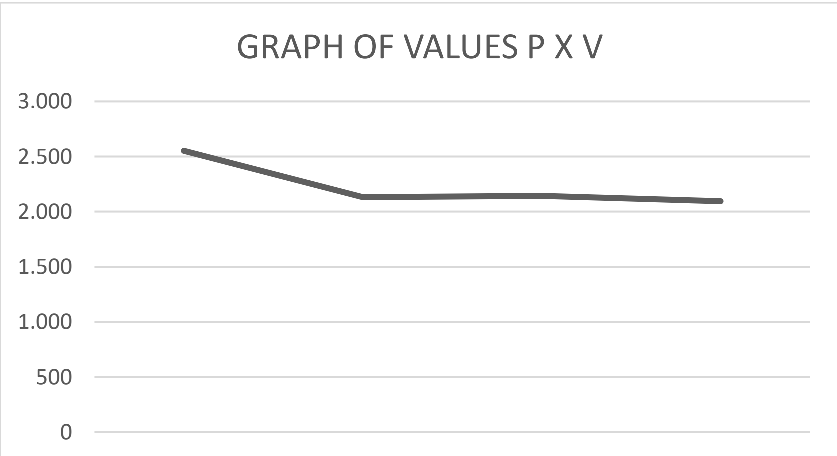

Figure 4. Graph of The Product of Pressure and Volume Values

Figure 4. displays a graph of the product of pressure and volume (P × V) obtained from experimental data at a constant temperature of 300 K. The horizontal axis represents the volume of the gas (V), while the vertical axis shows the product of pressure and volume (P × V).

This graph shows that the value of P × V tends to remain constant despite variations in the pressure and volume of the gas. This is in line with Boyle's law, which states that the product of the pressure and volume of a gas will remain constant for a fixed amount of gas at a constant temperature. This shows that the product remains constant if one variable (pressure or volume) increases and the other variable decreases (Pertiwi, 2022). For example, the data shows that although the pressure decreases as the volume increases, the product P × V remains at almost the same value, which can be seen in the P × V values listed in the previous table (for example, 2.552×10^{-18} Pa/m³ at a volume of 1.2×10^{-24} m³).

The basic principle of Boyle's law is clearly illustrated in this graph. The product of pressure and volume being constant shows an inverse relationship between the two variables. With this understanding, students will find it easier to comprehend and apply Boyle's law in physics experiments and in the real world (Pertiwi, 2022). The use of this graph in the PhET-based virtual laboratory also helps students to interactively observe and analyze how changes in pressure and volume contribute to the product P × V, enhancing their understanding of the concept of gas elasticity and the interaction between these variables in a gas system

In this study, the relationship between pressure (P) and volume (V) of a gas at constant temperature can be explained using Boyle's law, which is expressed in the following mathematical equation :

$$P \times V = K \quad (1)$$

where K is a constant that depends on the amount of gas and temperature. The data obtained from the experiment shows that the product of pressure and volume (P·V) remains constant, despite variations in the values of P and V. This can be seen from the calculation results, which indicate that the value of P·V remains close to the same value even though V increases, causing P to decrease, and vice versa. This consistent observation shows that all P·V values calculated from the experimental data (the table presented earlier) confirm that Boyle's law applies, reinforcing the basic concept taught in physics regarding the behavior of gases.

Further analysis of the graph showing the relationship between P and V also confirms that when V increases, P decreases, keeping the product P·V constant. The graphs shown in Figures 3 and 4 provide a clear visualization of how the interaction between the two variables aligns with equation (1), allowing students to intuitively understand this relationship. By using PhET-based simulations, students can more easily observe the dynamics of pressure and volume changes in real-time, providing a real context for the theoretical concepts taught in class.In the context of this research, it is important to further explain the constant K. The value of K is the result of the product of pressure and volume that remains constant for a certain amount of gas at a certain temperature. This research shows that the value of K obtained from the experimental results is consistent, indicating the validity of Boyle's law in this experiment. In addition, it is also important to note that potential errors in measuring pressure and volume should be taken into account. The accuracy of the instruments used in the experiment, such as the manometer, can affect the results obtained. For example, inaccuracies in reading the scale on the manometer can contribute to variations in the obtained results, thus emphasizing the importance of the calibration procedure before use (V. H. Putri, 2021).

The importance of maintaining a constant temperature during the experiment cannot be overlooked (Asmarani et al., 2024). Not only can temperature fluctuations affect the experimental results, but also the relationship between pressure and volume. In this study, the researchers ensured that the temperature remained stable during the observation to avoid inaccurate results. By controlling this variable, the researchers could distinguish the effects of volume changes on pressure, resulting in more accurate outcomes. In addition, Boyle's law is included in the ideal gas law, which states that PV=nRT. An explanation of the relationship between Boyle's law and the ideal gas law can provide a deeper understanding of gas behavior in a broader context.

Finally, this research makes a significant contribution to physics education in Indonesia by using PhET-based simulations. The simulation-based approach in the HOT Lab allows students to conduct experiments interactively, visualize variables, and develop critical thinking skills (Afdila & Sartika, 2020). Thus, students not only become consumers of information but also actively participate in the learning process; both roles are crucial for 21st-century education (David et al., 2021). Direct involvement in simulations gives students the opportunity to see and analyze in real-time how changes in one variable, such as volume, can affect another variable, such as pressure. This enhances their ability to think critically and improves their understanding of more complex physics concepts (Dewi, 2021). This study also shows that the use of simulations not only enhances a person's theoretical understanding but also helps them learn skills necessary for real life (Demboh & Susanti, 2021). Students can conduct experiments that might be difficult or impossible to perform in a physical laboratory with PhET (Cardoso et al., 2023).

This research is one of the first to evaluate the impact of simulation-based practical work in developing higher-order thinking skills in Indonesian physics education, providing valuable insights for modernizing science learning practices and promoting student-centered active learning. With results showing the effectiveness of this approach, it is hoped that more educational institutions will consider the implementation of simulations as part of their teaching strategies. Overall, this research not only provides evidence of the effectiveness of using PhET in learning Boyle's law, but also contributes to the development of better and more relevant learning methodologies in Indonesia, which can ultimately improve the quality of science education at the national level.

CONCLUSION

This study concludes that implementing a PhET-based virtual HOT Lab effectively enhances students' understanding of Boyle's Law by providing an interactive, inquiry-driven learning experience. Through real-time manipulation of gas variables, students gain a clearer conceptual grasp of the inverse relationship between pressure and volume at constant temperature. The virtual lab promotes active engagement and supports the development of critical and analytical thinking skills aligned with Higher Order Thinking principles.

Despite its strengths, the study is limited by its exclusive use of virtual simulations without comparison to physical laboratory experiences. Future research is recommended to examine the combined impact of virtual and physical lab activities, investigate the role of digital literacy in learning outcomes, and explore the effectiveness of hybrid lab formats. Expanding the use of PhET simulations in underserved educational settings may also offer insights into their potential to support equitable and scalable science education.

AKNOWLEDGMENT

The researcher expresses gratitude to the Physics Education Program at UIN Sunan Gunung Djati Bandung for the support and guidance provided throughout this study, in the form of knowledge, mentorship, and resources.

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