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Effectiveness of PhET Simulation in Acid–Base Practicum for Maritime Engineering Students: Alignment with IMO Model Course 7.04

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Abstract: This study aims to examine the effectiveness of PhET Simulation in acid–base practicums for maritime engineering students. The study addresses common challenges in basic chemistry practicums, including limited laboratory facilities, restricted practicum time, and students' low conceptual understanding. As a novel contribution, this study provides empirical evidence on the use of interactive virtual simulations in the context of maritime vocational education aligned with IMO Model Course 7.04. A pre-experimental one-group pretest–posttest design was employed involving 72 first-semester students. Data were collected using a validated and reliable multiple-choice test and analyzed using non-parametric statistical methods. The results indicate a significant improvement in students' learning outcomes after the implementation of PhET Simulation. These findings suggest that virtual laboratory simulations are an effective alternative to support conceptual understanding in acid–base learning. Furthermore, this study highlights the potential of integrating digital simulation tools into maritime chemistry education to support competency standards outlined in IMO Model Course 7.04.

Keywords: PhET simulation; virtual laboratory; acid-base; learning outcomes, IMO model course 7.04

INTRODUCTION

Chemistry learning plays a crucial role in vocational education as it provides the scientific foundation needed to support students' technical competencies. In maritime engineering education, mastery of basic chemical concepts—particularly acid–base chemistry is essential because it is directly

related to professional tasks in the maritime industry. According to the International Maritime Organization (IMO), specifically IMO Model Course 7.04 (Officer in Charge of an Engineering Watch/OICEW), engineering students are required to understand fundamental topics such as acid–base chemistry, corrosion, water testing and

treatment, and fuel characteristics as part of their professional competencies (IMO, 2014). Therefore, a solid understanding of acid-base concepts is necessary to support ship machinery operation, boiler and cooling water treatment, corrosion control, liquid waste management, and safe chemical handling.

Despite its importance, students often experience difficulties in understanding abstract acid-base concepts, including pH, ionization, acid-base strength, and neutralization reactions (Chang & Overby, 2014; Altmeyer et al., 2020). These challenges are further exacerbated by limited laboratory facilities, inadequate chemicals and measuring instruments, and restricted practicum time, particularly in Indonesian vocational institutions such as Politeknik Maritim Negeri Indonesia. As a result, students have limited opportunities to engage in hands-on experiments, which negatively affect their conceptual understanding (Hasibuan & Abidin, 2020) and science process skills (Subeki et al., 2022). In vocational education, where practical experience is essential, this limitation becomes a critical issue that needs to be addressed. Therefore, the use of appropriate learning media is necessary to facilitate clearer concept delivery (Agustina et al., 2023).

To address these challenges, the integration of digital technology in learning has become increasingly important in the Society 5.0 era (Lamb et al., 2017; Radianti et al., 2020). One promising approach is the use of virtual laboratories, which allow students to conduct experiments in a safe, flexible, and accessible environment. PhET Simulation, developed by the University of Colorado Boulder, provides interactive and visual-based science simulations that enable students to explore chemical phenomena dynamically (Wicaksono et al., 2020). Through features such as animation, variable manipulation, and microscopic visualization, PhET helps students understand abstract concepts more concretely. In addition, its accessibility across

devices makes it highly suitable for vocational learning environments.

Previous studies have demonstrated that PhET Simulation can improve students' conceptual understanding, analytical thinking skills (Dendodi, 2025), and learning outcomes in various disciplines, including chemistry (Al Fajri et al., 2016) and acid-base topics (Nurul Hikma et al., 2023). It has also been reported to enhance science process skills (Adilla, 2022; Subeki et al., 2022), critical thinking (Dendodi, 2025), learning independence (Erfianah et al., 2023), problem-solving skills (Rusdiana, 2019) and learning motivation (Jannah, 2020). Several classroom-based studies further indicate improvements in students' learning outcomes following the implementation of PhET simulations (Defianti et al., 2021; Hasibuan & Abidin, 2020; Widyaningsih & Yusuf, 2018). These findings consistently suggest that simulation-based learning is effective in supporting meaningful and interactive learning experiences (Fidan & Tuncel, 2019).

However, most existing studies have been conducted in general education contexts, such as secondary schools and non-specialized higher education, and have not specifically addressed the needs of vocational education (Radianti et al., 2020). In particular, limited research has examined the implementation of PhET Simulation in maritime engineering programs or explored its alignment with international competency standards such as IMO Model Course 7.04. This gap is significant because vocational education requires not only conceptual understanding but also alignment with industry-specific competencies relevant to professional practice.

Therefore, this study aims to address this gap by implementing PhET Simulation in acid-base practicums within a maritime vocational education context and evaluating its effectiveness in improving students' learning outcomes. Furthermore, this study examines the alignment of the learning approach with the competency standards outlined in IMO Model Course 7.04. By

integrating simulation-based learning with vocational competency requirements, this study offers a contextualized and practical approach to support the development of future ship engineering officers. This research is also expected to provide a blended practicum implementation model that is relevant to the needs of vocational education in the digital era, where creativity—particularly imagination skills—plays a crucial role in improving learning outcomes (Harefa & Sumiyati, 2024).

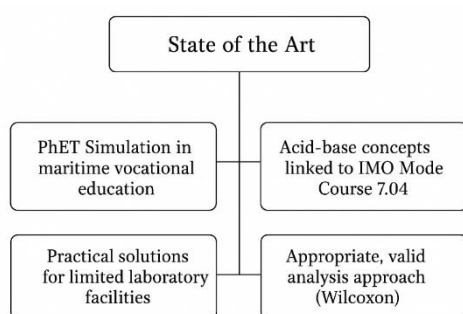


Figure 1. State of the Art

LITERATURE REVIEW

The acid–base concept is a fundamental topic in chemistry that underpins the understanding of solution properties, chemical reactivity, and various processes relevant to both everyday life and industrial applications. Classical theories, including Arrhenius, Brønsted–Lowry, and Lewis, provide complementary perspectives for explaining acid–base behavior at different levels of abstraction (Chang & Overby, 2014). Mastery of key concepts such as pH, ionization, acid–base strength, and equilibrium constants (K_a/K_b) is essential for students, particularly in vocational contexts. In maritime engineering education, these concepts are directly applied in corrosion control, boiler and cooling water treatment, and safe chemical handling, as required by IMO Model Course 7.04 (IMO, 2014). However, the abstract nature of these concepts often presents challenges for students, especially when practical learning opportunities are limited.

To address such challenges, virtual laboratories have been increasingly utilized as

alternative learning media. A virtual laboratory is a computer-based environment that simulates real experimental conditions, allowing students to perform experiments through interactive and visual representations (Razi, 2012). Compared to conventional laboratories, virtual labs offer several advantages, including flexibility, safety, cost efficiency, and the ability to repeat experiments without risk. More importantly, they support the visualization of abstract phenomena, which is critical in chemistry learning. Previous studies have shown that virtual laboratories can enhance conceptual understanding (Defianti et al., 2021; Hasibuan & Abidin, 2020), improve critical thinking skills (Dendodi, 2025), and increase student motivation (Sangaji Bagus, 2020). These findings highlight the potential of virtual laboratories to support meaningful learning experiences, particularly in resource-limited educational settings.

Among various virtual laboratory platforms, PhET Simulation has gained significant attention due to its interactive and inquiry-based design. Developed by the University of Colorado Boulder, PhET provides simulations that allow students to explore scientific concepts through experimentation, variable manipulation, and visualization (Sangaji Bagus, 2020). Based on constructivist learning principles, PhET encourages active learning and conceptual exploration. Previous research has demonstrated that PhET Simulation can improve students' conceptual understanding, problem-solving skills, and learning outcomes across various subjects. In the context of acid–base learning, PhET enables students to visualize pH changes, acid–base strength, and titration processes more effectively, thereby facilitating deeper conceptual comprehension.

In vocational education, learning is oriented toward the development of practical skills and competencies relevant to industry demands. Therefore, instructional approaches must not only support conceptual understanding but also enable students to apply knowledge in real-world contexts. In

maritime vocational education, this requirement is formalized through IMO Model Course 7.04, which emphasizes competency-based learning in areas such as chemical handling, safety, and environmental management (IMO, 2014). Consequently, learning media used in this context must align with both pedagogical needs and professional standards.

Despite the demonstrated effectiveness of virtual laboratories and PhET Simulation in general education, their application in vocational education—particularly in maritime engineering programs—remains limited. Existing studies tend to focus on secondary education or general science learning and rarely address the integration of simulation-based learning with industry-specific competency frameworks such as IMO Model Course 7.04. This indicates a gap between the potential of digital learning technologies and their contextual application in vocational maritime education.

Therefore, this study seeks to bridge this gap by examining the implementation of PhET Simulation in acid–base practicums within a maritime vocational context and analyzing its alignment with IMO Model Course 7.04 competencies. By integrating conceptual learning with professional standards, this study contributes to the development of a more contextualized and competency-oriented approach to chemistry learning in vocational education.

METHODS

This study employed a quantitative approach using a pre-experimental research design. Pre-experimental research involves a single group without a control group and utilizes pretest and posttest measurements to examine changes after treatment (Sugiyono, 2017). The design used in this study was a one-group pretest–posttest design, as illustrated in Table 1.

Table 1. Research Design

Pretest	Treatment	Posttest
O1	X	O2

The study involved one group of participants, namely first-semester Engineering students in the 2025/2026 academic year. Students were administered a pretest to measure their initial understanding, followed by treatment through the implementation of PhET Simulation as a virtual laboratory in the acid–base practicum of the Industrial Chemistry course. After the intervention, a posttest was conducted to measure improvements in learning outcomes (Damanik et al., 2024).

The research was conducted at the Engineering Department of Politeknik Maritim Negeri Indonesia during the odd semester of the 2025/2026 academic year. The population consisted of all first-semester students, with a total sample of 72 students from D-3 Engineering, D-4 Shipbuilding Engineering, and D-4 Mechatronics programs selected using saturated sampling. The independent variable in this study was the implementation of PhET Simulation in the acid–base practicum, while the dependent variable was students' learning outcomes measured through pretest and posttest scores.

The research instrument was a multiple-choice test consisting of 15 items for the pretest and 15 items for the posttest. The instrument was developed based on acid–base competencies outlined in IMO Model Course 7.04 and was validated through expert judgment involving chemistry lecturers and engineering instructors. Content validity was ensured by aligning the test items with learning indicators and competency standards. In addition, the reliability of the instrument was tested using internal consistency analysis, indicating that the instrument was reliable for measuring student learning outcomes.

Data were collected through pretests, posttests, and documentation of practicum activities. The research procedure was conducted in several stages: (1) preparation of learning materials and instruments, (2) administration of the pretest, (3) implementation of the PhET Simulation-based practicum, where students interacted with simulations to explore acid–base

concepts, (4) administration of the posttest, and (5) data analysis.

Data analysis was performed quantitatively using SPSS software. A Shapiro-Wilk test was conducted to assess data normality. Since the data were not normally distributed, the Wilcoxon Signed-Rank Test was used to examine differences between pretest and posttest results, with a significance level of 0.05.

Despite its strengths, this study has several limitations. The use of a one-group pretest-posttest design without a control group limits the ability to attribute changes in learning outcomes solely to the intervention, as external factors such as prior knowledge development or testing effects may influence the results. Additionally, the relatively small and context-specific sample may limit the generalizability of the findings. However, this design was considered appropriate for preliminary investigation in conditions with limited laboratory facilities and provides valuable insights for further experimental studies.

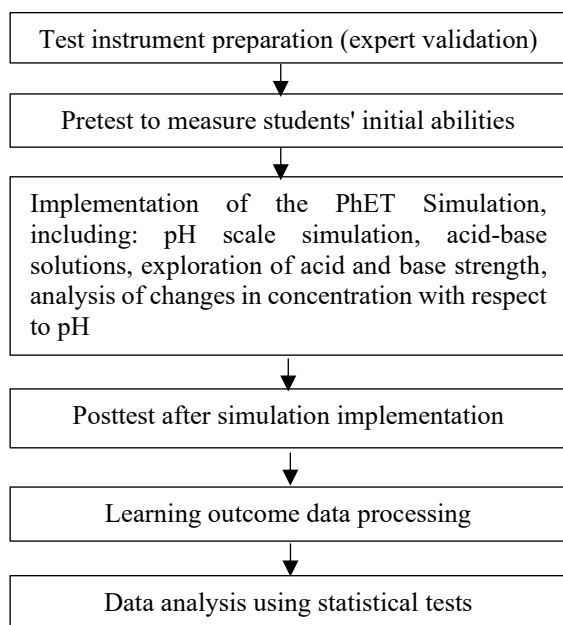


Figure 2. Research Procedure of PhET Simulation Implementation in Acid-Base Practicum

RESULT AND DISCUSSION

This study examined the effectiveness of PhET Simulation in improving students' learning outcomes in acid-base practicums.

The analysis was conducted using pretest and posttest data from 72 students.

Normality Test

The normality test results are presented in Table 2.

Table 2. Normality Test Results for Pretest and Posttest Scores

	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pre	.143	72	.001	.955	72	.012
Post	.165	72	.000	.950	72	.006

The Shapiro-Wilk test was used due to its suitability for small to medium sample sizes. The results showed that the significance values for both pretest ($p = 0.012$) and posttest ($p = 0.006$) were below 0.05, indicating that the data were not normally distributed. This suggests that students' performance varied considerably. This variation is likely due to differences in prior knowledge as well as the substantial impact of the intervention. Given the violation of normality assumptions, a non-parametric test was employed. The Wilcoxon Signed-Rank Test was selected as an appropriate method to analyze differences between paired observations.

Wilcoxon Signed-Rank Test

The Wilcoxon test results are presented in Tables 3 and 4.

Table 3. Distribution of Pretest and Posttest Score Differences

Category	N	Mean Rank	Sum of Ranks
Negative Ranks (Post < Pre)	5	10.10	50.50
Positive Ranks (Post > Pre)	65	37.45	2434.50
Ties (Post = Pre)	2	-	-
Total	72		

The results show that 65 out of 72 students demonstrated improved scores after the intervention, while only 5 students showed a decrease and 2 remained unchanged. This trend indicates a consistent positive shift in students' learning outcomes following the implementation of the simulation.

Table 4. Wilcoxon Signed-Rank Test Results

Statistics	Values
Z-score	-6.982
Asymp. Sig. (2-tailed)	0.000

The test yielded a Z value of -6.982 with a significance level of $p < 0.001$, indicating a statistically significant difference between pretest and posttest scores. To further assess the magnitude of the effect, the effect size (r) was calculated using the formula:

$$r = \frac{z}{\sqrt{N}}$$

Based on the calculation, the effect size was found to be $r = 0.82$, which indicates a large effect. This suggests that the improvement in student learning outcomes was not only statistically significant but also practically meaningful.

Descriptive Analysis

Table 5. Descriptive Statistics of Pretest and Posttest Scores

Variable	N	Mean	Std. Deviation	Std. Error Mean
Pretest	72	35.37	14.44	1.70
Posttest	72	69.07	20.15	2.37

The descriptive analysis shows a substantial increase in the mean score from 35.37 (pretest) to 69.07 (posttest), with a difference of 33.70 points. This improvement reflects a significant enhancement in students' conceptual understanding of acid-base topics.

This improvement indicates that students developed a stronger understanding of key acid-base concepts, including pH, ionization, and acid-base strength. The substantial shift in mean scores reflects not only cognitive gains but also a transition from fragmented understanding toward more integrated conceptual knowledge, which is aligned with the importance of interdisciplinary integration in enhancing students' higher-order and 21st century skills (Lei et al., 2026).

The findings demonstrate that the implementation of PhET Simulation has a significant and meaningful impact on students' learning outcomes in acid-base practicums. The large effect size ($r = 0.82$) confirms that the observed improvement is not only statistically significant but also substantial in practical terms.

This result can be explained through constructivist learning theory, which emphasizes that knowledge is actively constructed through interaction and exploration. The simulation environment allows students to manipulate variables and observe immediate outcomes, facilitating deeper conceptual understanding. In addition, simulation-based learning can be considered an innovative instructional approach that supports the development of knowledge, attitudes, and practical skills (Sukdee & Pechsri, 2026).

The findings are consistent with previous studies that reported improvements in conceptual understanding and learning outcomes through simulation-based learning (Dorji & Nima, 2025; Saragih & Dibyantini, 2024; Pardosi & Situmorang, 2024). However, this study extends previous research by demonstrating the effectiveness of PhET Simulation within a maritime vocational education context, where learning must align with practical competencies and industry standards.

From a practical perspective, the results indicate that simulation-based learning can serve as an effective alternative in institutions with limited laboratory facilities, while still providing opportunities for students to engage in experimental processes that are essential in chemistry learning (Seery, 2020). In this study, the use of PhET Simulation enabled students to experience experimental processes virtually, which supported their understanding of concepts relevant to maritime applications, such as corrosion control and water treatment. This alignment with IMO Model Course 7.04 highlights the relevance of the approach in preparing students for real-world engineering tasks.

Despite the overall positive results, a small number of students did not show improvement, which may be attributed to differences in learning styles, levels of engagement, or familiarity with digital tools. This suggests that while simulation-based learning is effective, it should be

complemented with appropriate instructional guidance to maximize its impact.

Building upon these findings, it is important to examine how the improvement in conceptual understanding aligns with the competency requirements in maritime vocational education.

Relevance of Acid-Base Material to IMO Model Course 7.04

Acid-base concepts involve multiple levels of representation, including macroscopic (observable changes), microscopic (ions and molecular interactions), and symbolic (chemical equations). These multi-level representations are often difficult for students to integrate, particularly when learning relies on conventional instructional methods (Chang & Overby, 2014; Johnstone, 1997). The findings of this study indicate that students' improved learning outcomes can be attributed to their enhanced ability to connect these representations into a more coherent conceptual framework. This supports previous studies showing that interactive simulations can facilitate integrated understanding of abstract chemical concepts (Widiastari & Redhana, 2021).

The significant improvement in students' scores (mean increase of 33.70 points, $p < 0.001$) suggests that the learning approach effectively supports conceptual development. This finding is consistent with previous research demonstrating that simulation-based learning enhances conceptual understanding and learning outcomes across various domains (Ika Septiana, 2020; Al Fajri et al., 2016). Moreover, the effectiveness of this approach can be explained through constructivist learning theory, where students actively construct knowledge through interaction, exploration, and feedback (Dendodi, 2025; Laila, 2022). However, this study extends prior research by situating the implementation within a maritime vocational context, thereby addressing a gap in the application of

simulation-based learning in industry-oriented education.

In the context of maritime education, acid-base knowledge is not only theoretical but also directly linked to professional competencies required under IMO Model Course 7.04. These include applications in boiler and cooling water treatment, corrosion prevention, chemical handling, and occupational safety in machinery systems (IMO, 2014). The improvement in students' conceptual understanding observed in this study indicates that they are better prepared to understand these applications at a foundational level. In other words, strengthened conceptual knowledge serves as a prerequisite for developing applied technical competencies.

Table 6. Alignment of Acid-Base Concepts with IMO Model Course 7.04 Competencies

Chapter	Subchapter
Fundamentals (Chemistry)	Atoms, molecules, matter, elements, compounds, mixtures, chemical reactions, oxide compounds, chemical equation conventions, and solutions
Acidity/Alkalinity	Atomic composition, acid-base theory, hydrogen ions, hydroxyl ions, pH value, and acid-base strength
Corrosion	Definition of corrosion, corrosion mechanisms, corrosion components, types of corrosion, corrosion factors, seawater and corrosion, boiler water, corrosion control, and passive coatings
Water testing and treatment	Relevance to IMO, ballast water, wastewater, boiler water, drinking water, steam boilers, ship corrosion and scaling systems, pH and minimum corrosiveness, chemical additives, seawater conditioning methods, standard units of measurement, water hardness, and water testing and treatment
Fuels and lubricants	Concepts of fuel, marine fuels, marine lubricants, the importance of fuels and lubricants, flash point, viscosity, the importance of flash point and viscosity, fuel temperature regulation, fuel and lubricant testing, testing of water content in fuel, and fire prevention fire

The mapping presented in Table 6 demonstrates that acid-base concepts are

embedded across multiple competency areas, particularly in water treatment and corrosion control. This indicates that mastery of these concepts is essential for understanding operational processes in maritime systems. Therefore, improving students' comprehension of acid–base chemistry contributes directly to their readiness to meet professional standards.

From a pedagogical perspective, the findings suggest that simulation-based learning can serve as an effective bridge between abstract conceptual knowledge and applied vocational competencies. However, it is important to note that while the simulation supports conceptual understanding, it does not fully replicate the complexity of real maritime systems. As such, the use of PhET Simulation should be complemented by contextual and practice-based learning activities that emphasize real-world applications, such as case-based learning or hands-on training in actual laboratory or industrial settings.

between ion concentration, pH values, and acid–base strength through dynamic and interactive representations. This multi-level visualization plays a critical role in reducing the abstract nature of chemical concepts, enabling students to establish clearer relationships between theoretical representations and observable phenomena (Chang & Overby, 2014; Johnstone, 1997).

These features provide meaningful learning experiences by allowing students to explore key concepts such as ionization processes, solution concentration, and pH changes in a controlled virtual environment. This supports the earlier findings of this study, where the significant improvement in learning outcomes indicates that students were able to develop a more coherent conceptual understanding.

However, consistent with the previous discussion, it is important to emphasize that the simulation primarily supports foundational conceptual learning. It does not fully represent the complexity of real maritime engineering applications, such as pH regulation in boiler systems or corrosion control in ship machinery. Therefore, the simulation should be positioned as a foundational learning tool that supports conceptual understanding, which must be further reinforced through applied and context-based instruction to fully meet the competency demands of maritime engineering practice.

CONCLUSION

This study confirms that PhET Simulation is effective in improving students' conceptual understanding of acid–base topics in maritime vocational education. The use of interactive simulations helps visualize abstract concepts and supports more meaningful learning experiences.

Pedagogically, this finding highlights the potential of simulation-based learning as an alternative to conventional laboratory practices, particularly in contexts with limited facilities. In addition, the alignment with IMO Model Course 7.04 indicates that such

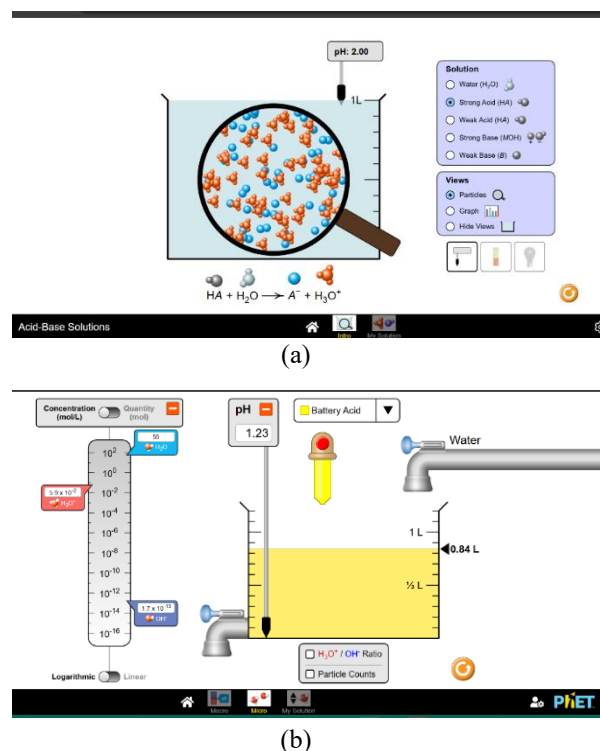


Figure 3. PhET Simulation Interfaces for Acid–Base Learning (a) Conceptual Visualization, (b) pH Determination

As shown in Figure 3, the simulation enables students to observe relationships

approaches can support the development of competencies relevant to maritime engineering practice.

However, this study is limited by the use of a pre-experimental design and its focus on short-term learning outcomes. Future research should employ more rigorous designs and explore the integration of simulations with hands-on or industry-based learning to enhance practical competencies.

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