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The effect of the mobile learning–based PhET interactive simulation approach on students' conceptual learning and creative thinking in the concept of solutions

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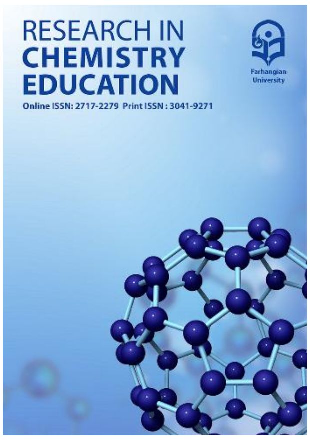

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Abstract:

Background and Objective: This study aimed to examine the impact of the Mobile Learning–based PhET Interactive Simulation (ML-PhET) approach on conceptual learning and creative thinking among tenth-grade students studying solutions. By combining mobile learning with PhET simulations, the ML-PhET approach offers an innovative framework for chemistry education that emphasizes self-directed, interactive, and experiential learning. **Methods**: A quasi-experimental design was employed, featuring pretest, posttest, and follow-up assessments. The participants were tenth-grade female students from Isfahan during the 2024–2025 academic year. Data collection involved a researcher-developed academic achievement test to evaluate Bloom's four cognitive domains and a creativity questionnaire based on Guilford's model. Experts in chemistry and educational sciences confirmed the content validity of both instruments, and their reliability coefficients, as measured by Cronbach's alpha, were 0.81 and 0.80, respectively. Data analysis utilized Wilcoxon and Mann–Whitney tests, with Bonferroni correction applied. **Findings**: The ML-PhET approach significantly enhanced students' performance across Bloom's cognitive domains, including Knowledge, Comprehension, Application, and Analysis, with these effects persisting even after 60 days. Notable improvements were also found in the creativity components of Fluency, Originality, and Sensitivity, while Flexibility and Elaboration showed no significant change. **Conclusion:** The findings suggest that the ML-PhET approach effectively enhances both conceptual learning and creative thinking, providing a practical and innovative alternative to traditional chemistry instruction.

Keywords: Chemistry education, conceptual learning, creative thinking, mobile learning, PhET Interactive Simulation, STEM

Introduction

In today's rapidly evolving world, where knowledge and technology advance at an unprecedented pace, educational systems urgently need approaches that prepare future generations to tackle complex, real-life challenges. In this context, conceptual learning of scientific knowledge is essential not only for comprehending natural phenomena and achieving academic success but also for developing skills that extend beyond rote memorization. Science education, particularly in chemistry, is vital to this process. Chemistry lays the groundwork for understanding the structure and behavior of matter while also connecting the natural sciences, technology, and everyday life. Mastering chemical concepts is crucial for academic achievement, pursuing related university disciplines, and effectively participating in a knowledge-based society. In line with the objectives of Science, Technology, Engineering, and Mathematics (STEM) education, chemistry instruction should be structured not only to enhance understanding of scientific concepts but also to develop analytical skills, problem-solving abilities, and creative thinking (Akrami, 2022). A crucial aspect of effective learning is the focus on Bloom's cognitive domains, which encompass Knowledge (memorization of basic concepts), Comprehension (the ability to explain and interpret scientific relationships), Application (utilizing concepts in new contexts), and Analysis (breaking down problems into components and examining their interconnections) (Doronina et al., 2024). True conceptual learning is achieved only when these levels are reinforced simultaneously. In addition to conceptual learning, fostering creative thinking has become essential in modern education, as it empowers learners to generate diverse ideas, think flexibly, devise innovative solutions, and expand on initial concepts. According to Guilford's theory of creativity (1950), creative thinking involves several key abilities: Fluency (the capacity to produce multiple ideas in response to a problem or stimulus), Flexibility (the ability to shift perspectives and propose varied solutions), Originality (the capacity to generate novel ideas that are less likely to occur to others), Elaboration (the ability to provide detailed explanations and further develop an initial idea), and Sensitivity (the ability to identify issues and pay attention to details or deficiencies in a situation). These skills enable students to propose innovative solutions to scientific and social challenges. Empirical studies, such as those by Fadillah et al. (2025) and Siswanto et al. (2025), have shown that integrating conceptual learning with creativity development creates a strong foundation for nurturing independent and creative learners.

Traditional education faces significant limitations in achieving its goals. In this approach, learners take a predominantly passive role, with the process primarily focused on the linear transmission of information from teacher to student. This method neglects the discovery and construction of knowledge by the learner. Additionally, the lack of opportunities for experimentation, exploration, and critical thinking results in students acquiring scientific concepts superficially, relying on rote memorization instead of understanding the connection between theoretical knowledge and real-world applications. Ultimately, these limitations hinder the development of divergent thinking, innovation, and problem-solving skills, weakening the foundation for scientific creativity within traditional educational environments (Krathwohl, 2002).

The Mobile Learning approach based on the PhET Interactive Simulation (ML-PhET) offers an innovative framework for STEM education that fosters a dynamic and self-directed learning environment. Rooted in Constructivism (Sayaf, 2023) and Experiential Learning (Alwafi, 2025), this approach positions students as active participants in constructing knowledge. By engaging continuously with multimedia content and authentic simulations, learners can transform abstract concepts into tangible experiences. The PhET (Physics Education Technology) simulation, built on conceptual models and empirically validated scientific data, allows learners to manipulate variables, observe outcomes, and test hypotheses, guiding their learning in an exploratory and creative manner. Additionally, the portability and accessibility of mobile learning free education from the constraints of time and space, enabling learning to extend beyond the formal classroom into informal settings. This integration of interactivity, flexibility, and experiential engagement not only fosters deeper conceptual understanding but also enhances creative thinking, problem-solving, and scientific innovation among learners, outcomes that traditional education, with its linear and non, interactive structure, often fails to achieve.

Numerous studies have reported the effectiveness of both PhET simulations and mobile learning in enhancing the understanding of fundamental chemistry concepts. Hurst et al. (2025) and Clark (2024) demonstrated that using the PhET interactive simulation to teach molecular polarity significantly improves students' comprehension of greenhouse gases and their role in global warming. Similarly, Moore et al. (2014) and Clark & Chamberlain (2014) found that employing this simulator for teaching the atomic model of hydrogen and Beer's Law enhances students' understanding of quantum models. In addition, Salame & Makki (2021) showed that the interactive PhET environment boosts students' intrinsic motivation and their willingness to actively explore general chemistry content. Likewise, Kizito & Hassan (2024) argued that PhET, by offering an intuitive platform for visualization and interaction with scientific concepts, enhances students' conceptual understanding of complex topics such as chemical bonding, gas laws, chemical equilibrium, and electrochemistry. Beyond conceptual learning, the role of PhET in fostering problem-solving skills and creativity has also been highlighted. For instance, Maesaroh & Sutikno (2025) reported that integrating interactive simulations with classroom activities improved students' creative thinking components, particularly fluency and originality. Similarly, Sharifzadeh & Ahmadabadi (2025) found that using PhET simulations led to higher academic scores, increased motivation, a reduction of misconceptions, and a deeper understanding of scientific principles.

In another study, Azemat (2023) concluded that incorporating simulation-based innovations in chemistry instruction can enhance student enthusiasm and make learning more engaging and enjoyable. Furthermore, Diab et al. (2024) found that using PhET to teach the concept of solubility significantly increased students' participation and reasoning skills. From a comparative perspective, several studies indicate that the conceptual understanding achieved through simulations can be comparable to or even more effective than traditional laboratory instruction. For example, Ndagijimana et al. (2025) reported that students taught with the PhET simulator in their study on chemical reactions, acids, bases, and pH demonstrated greater accuracy in calculations and a stronger grasp of concepts than those taught through conventional methods. Akrami et al. (2025) identified educational simulations as one of the most effective tools for implementing mobile learning in chemistry education. In a subsequent study, Akrami & Shirvani (2025) demonstrated that simulating the concepts of mixtures and factors influencing dissolution rate using smartphones (as an instrument of mobile learning) can significantly enhance students' conceptual learning and engagement.

Sharifzadeh and Ahmadabadi (2025) demonstrated that technology can improve learning and reduce misconceptions about subatomic structures among lower-secondary students. Moradi and Arasteh Saleh Kohi (2023) found that enriching the learning environment with PhET interactive simulations leads to a purposeful and intelligent integration of technology in the chemistry curriculum, which boosts learning and academic engagement in the concept of atomic structure among tenth-grade students. Similarly, Sharifati et al. (2021) concluded that the use of PhET interactive simulations in chemistry instruction significantly improves spatial ability and problem-solving skills in tenth-grade female students.

Learning the topic of solutions is one of the most challenging aspects of secondary-level chemistry education due to its inherently multidimensional nature, which requires grasping abstract, quantitative, and particulate concepts simultaneously. Research shows that many students struggle with the dissolution process, the distribution of particles in a solution, and differentiating among concentration, volume, and mass. Students also find it difficult to apply mathematical relationships related to molarity, mass percent, and parts per million (Suparman et al., 2025). Furthermore, Akgün (2009) found that students often fail to connect different representations of solution concepts, leading to conceptual misunderstandings. Additional studies indicate that difficulties in transitioning between representational levels hinder students' comprehension of the relationships among the amounts of substances, concentration, and proportionality (Talanquer, 2022). In this context, interactive tools can help alleviate some of these challenges. Educational simulations like PhET allow students to dynamically visualize abstract processes related to solutions, manipulate variables that affect concentration, and observe the outcomes of these changes across various representations (Kizito & Hassan, 2024). Moreover, mobile learning provides continuous and flexible access to resources, enabling students to repeatedly review complex concepts and engage with the material, which is crucial for internalizing abstract ideas and their quantitative relationships. Studies by Akrami and Shirvani (2025) have shown that mobile learning, through microlearning activities, step-by-step exercises, short animations, and immediate quizzes, can reduce cognitive load and enhance understanding of chemical concepts. These features not only lower cognitive demands but also foster deeper conceptual understanding and the development of more accurate mental models.

Despite the rapid growth of mobile learning and interactive technologies in science education, significant gaps remain in understanding their impact on deep learning and creative thinking. Most previous studies have focused solely on the effects of educational simulations on enhancing conceptual understanding, scientific attitudes, or student motivation, with few exploring learning across the full spectrum of Bloom's cognitive taxonomy, namely knowledge, comprehension, application, and analysis. This limitation is particularly critical when teaching foundational chemistry concepts like solutions, which require students to transition between different representations, understand mathematical relationships, and engage in problem-solving skills that traditional instructional methods are less likely to foster. Furthermore, while simulations like PhET can stimulate observational processing, exploratory inquiry, and experimental reasoning, few studies have investigated their effects on the five components of creative thinking (Fluency, Flexibility, Originality, Elaboration, and Sensitivity), and existing research has typically focused on only one of these dimensions. Additionally, most studies have measured outcomes immediately after the intervention, leaving a lack of empirical evidence regarding the long-term retention of educational effects. Content-wise, PhET-based research has primarily concentrated on topics such as chemical reactions (Ndagijimana et al., 2025), acids and bases (Nuraida et al., 2021; Buhera et al., 2024), and stoichiometry (Aliyu, 2025), while the topic of solutions has not yet been explored using this simulator. To address these theoretical and empirical gaps, the present study introduces an innovative integrated approach called ML-PhET, which combines mobile learning with interactive simulations within a unified instructional framework. This approach positions the simulator as a core component of the teaching-learning process rather than merely a supplementary tool, facilitating free interaction, self-directed learning, and experiential exploration. This study examines the effects of the ML-PhET approach on the four cognitive levels of Bloom's taxonomy and on Guilford's five components of creative thinking. Unlike previous research that concentrated on only one aspect of learning or creativity, this study provides a multidimensional, differentiated, and comprehensive view of how technology contributes to cognitive and creative development. Additionally, utilizing three assessment points (pre-test, post-test, and follow-up) allows for the analysis of retention and the sustainability of cognitive and creative changes, representing a methodological advancement over existing literature. The purpose of this study is to evaluate the effectiveness of the ML-PhET approach in teaching the concept of solutions at the four cognitive levels of Bloom's taxonomy, as well as enhancing the five components of creative thinking among tenth-grade students. It aims to assess not only the short-term effects but also the long-term persistence of these changes. In doing so, this research seeks to fill existing gaps in the literature and provide robust empirical evidence regarding the role of interactive technologies in enhancing conceptual learning, cognitive performance, and creativity in chemistry education. To align with these objectives, the study addresses the following hypotheses:

1. The ML-PhET approach significantly enhances tenth-grade students' learning levels regarding the concept of solutions.
2. The ML-PhET approach significantly enhances tenth-grade students' creative thinking regarding the concept of solutions.

Examining these hypotheses can fill the current gap in the research literature and provide a practical model for designing innovative educational programs within the international educational system. Additionally, it can serve as a guideline for teachers and policymakers to improve the quality of chemistry education and foster the development of students' creative skills.

Methodology

This study utilized a quasi-experimental design with a practical focus, employing a pretest and posttest design with a follow-up phase that involved the experimental and control groups.

Participants

The statistical population comprised all tenth-grade high school students in Isfahan City during the 2024–2025 academic year. The sample size was calculated using G*Power statistical software based on a repeated-measures ANOVA test at a significance level of 5% ($\alpha = 0.05$), with a test power of 80% ($\beta = 0.2$) and a medium effect size ($d = 0.3$), resulting in a total of 250 students (125 per group) (Kang, 2021). To mitigate participant attrition, 260 female students were selected through convenience sampling and randomly assigned to two equal groups: the ML-PhET group and the control group. Inclusion criteria specified participants aged 15 to 16 years, currently enrolled in the tenth grade, actively participating in a chemistry course, demonstrating sufficient academic and cognitive competence (particularly in basic mathematical skills), and providing informed consent to participate.

Exclusion criteria included lack of cooperation, failure to complete assigned learning activities, and absence from more than two sessions. To maintain group equivalence, participants were assessed for variables such as age, cultural similarities, and prior knowledge of the subject matter. Participation was voluntary, and students could withdraw at any time. Ultimately, 126 students in the ML-PhET group ($M_{age} = 15.37 \pm 0.46$; Chemistry grade = 17.40 ± 2.03) and 128 students in the control group ($M_{age} = 15.42 \pm 0.21$; Chemistry grade = 17.32 ± 2.17) completed the study and participated in the final phase of data collection.

Instructional Framework

The concept of solutions and its related sub-concepts including molarity, mass percent, the calculation of solution concentration in various units, and the preparation of dilute solutions from concentrated ones are covered in high school chemistry textbooks. This topic builds on the understanding of homogeneous mixtures and serves as a foundation for more advanced concepts such as the effect of concentration on reaction rates, acid-base, chemical equilibrium, and stoichiometry. In this study, the concept of solutions was taught to students in the ML-PhET group using the Mobile Learning based PhET interactive simulation approach. In contrast, students in the control group received traditional lecture-based instruction. The instructional framework of the ML-PhET approach was developed in accordance with the theoretical foundations of mobile learning and structured into four sequential steps, including *Activation, Browsing, Conceptualization, and Deployment*. These steps aimed to enhance students' cognitive levels and creativity through interaction, exploration, and meaningful learning.

Figure 1 and Supporting Information illustrate the instructional framework of the ML-PhET approach implemented in this study.

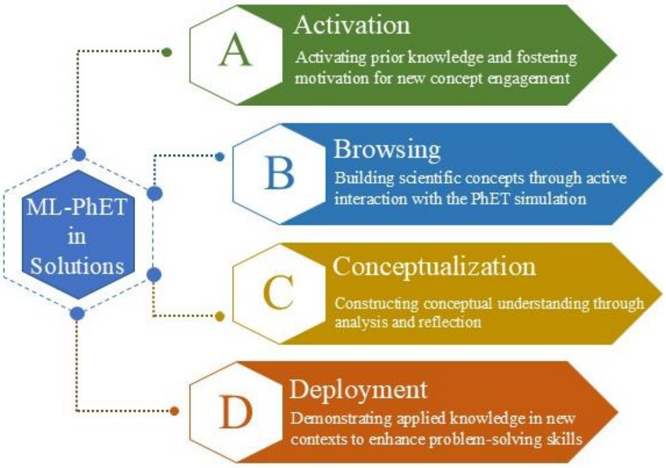

Figure 1- Instructional framework of the ML-PhET approach

The instructional content was delivered to students over eight 45-minute sessions. To maintain treatment fidelity, the researcher and instructor were the same individual, and both groups received instruction under identical teaching conditions. The instructional resources and topics were consistent for both groups, drawn from the Grade 10 Chemistry textbook used in the national curriculum. In the ML-PhET group, instruction was conducted using the ML-PhET approach. With the coordination of the school principal and following a predefined protocol, students were allowed to bring their mobile phones into the classroom during specific sessions. Mobile phone use was restricted to educational activities and required direct supervision from the teacher. In the first session, the teacher provided step-by-step instructions on accessing the PhET simulator, setting it up, and completing the assigned tasks. Each instructional session included three parts: (1) initial guidance from the teacher, (2) individual or group exploratory activities in the simulation environment using mobile phones, and (3) a whole-class discussion to analyze the simulated scenarios and summarize key concepts. During their time with the simulator, students manipulated various parameters, such as solute amount, solution volume, and concentration, and observed and recorded the resulting changes. Table 1 outlines the structure and content of the educational activities designed for the ML-PhET group.

Table 1- The Structure and Content of the ML-PhET Educational Activities Designed

Educational Aim	**Conceptual Learning Activity**	**Creative Thinking Activity**
Session 1- Step A: Establishing a connection between prior knowledge and the new learning context, and activating intrinsic motivation		
Assessing prior knowledge before implementing the activity	Students individually participate in the learning pre-test	Students individually participate in the creative thinking pretest
Session 2- Step B: Engaging in exploratory and self-directed learning		
- Teaching the sub-concept of solution components **- Developing the idea generation component**	Preparing various types of solutions using the PhET interactive simulator on mobile devices	Creating a list of different types of solutions, providing one example for each, and categorizing their ideas accordingly
Session 3- Step C: Transitioning from experience to abstract thinking and deepening conceptual understanding		

- Teaching the sub-concept of molar concentration and its method of calculation **- Developing the flexibility component**	Calculating concentration using the PhET mobile simulator and comparing results with their own manual calculations	Solving a single problem through multiple methods, such as mathematical computation, direct use of simulator data, and plotting graphical representations
Session 4- Step C: Transitioning from experiential engagement to abstract thinking and deepening conceptual learning		
- Teaching the sub-concept of mass percent and its calculation method **- Developing the originality component**	Altering the mass of the solute and solvent and examining its effect on the solution's mass percent	Presenting a creative method for demonstrating or explaining the mass percent of a solution
Session 5- Step B: Engaging in exploratory and self-directed learning		
- Teaching the sub-concept of parts per million (ppm) and its calculation method **- Developing the elaboration component**	Investigating the effect of solute and solvent mass on solution concentration	Selecting an initial idea and expanding it using practical examples and simulation-generated data
Session 6- Step C: Transitioning from experiential engagement to abstract thinking and deepening conceptual understanding		
- Teaching the sub-concept of dilution and its calculation method **- Developing the sensitivity component**	Using the PhET interactive simulator on a mobile device to dilute a concentrated solution to a specific concentration	Receiving a scenario, identifying procedural errors and their potential consequences, and proposing corrective strategies
Session 7- Step D: Consolidating learning and creative thinking		
Assessing acquired knowledge after the completion of the instructional activity	Students individually participate in the posttest of learning	Students individually participate in the posttest of creative thinking
Session 8- Step D: Consolidating learning and creative thinking		
Assessing knowledge retention sixty days after the implementation of the activity	Students individually participate in the follow-up of learning	Students individually participate in the follow-up of creative thinking

Research Instruments

Student learning achievement was assessed using a researcher-developed academic achievement test. The concept of solutions was evaluated through 12 open-ended questions that addressed the four cognitive domains of Bloom's taxonomy, including Knowledge (Q_1-Q_3), Comprehension (Q_4-Q_6), Application (Q_7-Q_9), and Analysis (Q_{10}-Q_{12}), with three questions per domain. Each question focused on a sub-concept of the solutions topic, including solution components (3 questions), molar concentration (3 questions), mass percent (2 questions), parts per million (ppm) (2 questions), and dilution (2 questions). The content validity of the test items was verified by two university faculty members in chemistry and three chemistry teachers. The reliability of the researcher-developed test was calculated using Cronbach's alpha coefficient (α), resulting in a reliability index of 0.811, which indicates satisfactory internal consistency (Cronbach & Shavelson, 2004).

The assessment of students' creative thinking was conducted using a researcher-developed questionnaire based on Guilford's theory of creativity. The questionnaire comprised 30 items, rated on a five-point Likert scale, covering five components including Fluency, Flexibility, Originality, Elaboration, and Sensitivity with six items dedicated to each component. The content and face validity of the questionnaire were evaluated and confirmed by seven university faculty members (two in Chemistry and five in Educational Sciences). The reliability of the questionnaire was estimated using Cronbach's alpha coefficient ($\alpha = 0.803$), indicating a high level of internal consistency among the items.

The same set of learning test and creative thinking questionnaire items were administered to both the ML-PhET and control groups at three stages: pretest, posttest, and 60-day follow-up after the instructional intervention. The student response rate was 100%, with no missing data. The learning assessment and the creative thinking questionnaire tests items are provided in the Supporting Information.

Analysis

To compare the mean age and average grade in chemistry between the two groups, we initially assessed the normality of data distribution using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Based on these results, we proceeded with an independent samples t-test. The Wilcoxon test and the Mann–Whitney test, applying a Bonferroni correction to control for Type I error in both within-group and between-group comparisons were utilized. Statistical analyses were performed using IBM SPSS Statistics 26. Adjusted *p*-values are reported as p_{adj} and were computed using Bonferroni correction ($p_{\text{adj}} = p \times k$, where k is the number of comparisons). Effect size (ES) for between-group comparisons was calculated as Cohen's d using pooled standard deviations (d = Δ/Sp (where Δ = Mean difference, $S_p = \sqrt{(((N_1-1)\, S_1^2 + (N_2-1)\, S_2^2)/ (N_1+N_2-2)))}$, N_1: Number of students in ML-PhET group, N_2: Number of students in control group, S_1: standard deviation of ML-PhET score, and S_2: Standard deviation of control group score).

Results

The students in the ML-PhET and control groups were assessed for homogeneity in demographic variables, specifically age and average grades in chemistry. The Kolmogorov–Smirnov and Shapiro–Wilk tests were employed to evaluate the normality of the distribution of these demographic variables (Table 2). Following the recommendations of Levin et al. (2017) for small datasets ($N < 2000$), both tests were applied to ensure robustness.

Table 2- Normality tests for demographic background in the ML-PhET and control groups

Group	Demographic Dimension	Kolmogorov-Smirnov		Shapiro-Wilk	
		Statistic	*p*	Statistic	*p*
ML-PhET (N = 126)	Age	0.43	0.121**	0.95	0.422**
	Average grade in chemistry	0.50	0.277**	0.91	0.171**
Control (N = 128)	Age	0.91	0.105**	0.94	0.308**
	Average grade in chemistry	0.86	0.362**	0.90	0.289**

** $p > 0.05$

As shown in Table 2, the significance levels for both demographic variables in the ML-PhET and control groups exceeded 0.05, indicating a normal distribution for age and average grades in chemistry. Consequently, an independent samples t-test, a parametric test, was utilized to assess the homogeneity of the demographic variables between the two groups prior to the intervention (Table 3).

Table 3- Independent samples t-Test for demographic background in the ML-PhET and control groups

Group	Demographic Dimension	Min	Max	Mean	t	*p*
ML-PhET (N = 126)	Age	15.00	17.00	15.37±0.46	1.65	0.105**
	Average grade in chemistry	4.27	19.35	17.40±2.03		
Control (N = 128)	Age	15.00	17.00	15.42±0.21	0.97	0.329**
	Average grade in chemistry	8.71	18.89	17.32±2.17		
** $p > 0.05$						

The results of the independent samples t-test revealed no statistically significant difference between the two groups concerning mean age ($p = 0.105$) and average grades in chemistry ($p = 0.329$). Thus, it can be concluded that the two groups were homogeneous before the intervention.

Hypothesis 1: The ML-PhET approach significantly enhances tenth-grade students' learning levels regarding the concept of solutions.

H0: There is no significant difference in students' learning levels of the concept of solutions when comparing the ML-PhET approach to the traditional teaching method.

H1: There is significant difference in students' learning levels of the concept of solutions when comparing the ML-PhET approach to the traditional teaching method.

The pretest, posttest, and follow-up scores for learning of the concept of solutions in the ML-PhET and control groups were tested for normality using the Kolmogorov–Smirnov and Shapiro–Wilk tests (Table 4).

Table 4- Normality test for learning variable in ML-PhET and control groups at the pretest, posttest, and follow-up

Group	Test	Kolmogorov-Smirnov		Shapiro-Wilk	
		Statistic	*p*	Statistic	*p*
ML-PhET (N = 126)	Pretest	0.57	0.021*	0.92	0.032*
	Posttest	0.74	<0.001*	0.86	0.002*
	Follow-up	0.52	0.017*	0.72	0.001*
Control (N = 128)	Pretest	0.86	0.001*	0.81	0.028*
	Posttest	0.83	0.003*	0.93	0.007*
	Follow-up	0.51	0.002*	0.47	0.029*
* $p < 0.05$					

Both of Kolmogorov–Smirnov and Shapiro–Wilk tests indicated significant deviations from normality ($p < 0.05$). So, we adopted nonparametric procedures in line with recent recommendations for educational data analysis in chemistry education (Sequeira & Borges, 2024). Following best practices for nonparametric analyses, the Wilcoxon and Mann–Whitney tests with Bonferroni correction were used for pairwise comparisons between and within group, respectively. Table 5 presents the results of within-group and between-group comparisons across the four cognitive domains of Bloom's taxonomy related to the concept of solutions among students in the ML-PhET and control groups.

Table 5- Between and within group comparisons of Bloom's taxonomy mean scores in ML-PhET and control groups

	Pretest	Posttest	Follow-up	Pretest- Posttest			Posttest- Follow-up		
	M±SD	M±SD	M±SD	Δ±SD	p_{adj}^{a}	ES	Δ±SD	p_{adj}^{a}	ES
				Knowledge					
ML-PhET	1.87±0.35	11.04±0.86	10.98±1.05	9.17±1.12	0.002*	8.81	0.06±0.02	0.297	0.05
Control	1.78±0.92	7.68±0.72	7.57±1.20	5.90±1.84	0.007*	8.00	0.11±0.61	0.459	1.00
Δ±SD	0.09±0.13	0.36±0.08	3.41±0.26						
p_{adj}^{b}	0.082	0.213	0.117						
ES	0.58	0.47	1.10						
				Comprehension					
ML-PhET	1.36±0.46	10.10±1.83	10.06±1.18	8.74±1.63	0.002*	5.33	0.04±0.02	1.867	0.03
Control	1.42±0.64	8.09±1.57	8.12±1.42	6.67±2.04	0.003*	4.64	0.03±0.01	0.520	0.02
Δ±SD	0.06±0.02	2.01±0.54	1.94±0.26						
p_{adj}^{b}	1.020	0.007*	0.009*						
ES	0.29	1.83	1.96						
				Application					
ML-PhET	0.90±0.75	10.11±0.17	10.53±1.12	9.21±2.43	0.001*	11.15	0.42±0.14	0.094	0.33
Control	0.87±0.31	8.32±1.69	8.28±1.26	7.45±2.29	0.010*	4.85	0.04±0.02	0.324	0.02
Δ±SD	0.03±0.01	1.79±0.73	2.25±0.701						
p_{adj}^{b}	0.975	0.008*	0.031*						
ES	0.06	1.47	1.60						
				Analysis					
ML-PhET	0.71±0.14	9.97±1.84	10.05±1.27	9.26±3.08	0.003*	5.32	0.08±0.03	0.223	0.05
Control	0.75±0.25	7.13±1.15	6.68±1.79	6.38±2.10	0.009*	4.05	0.45±0.70	0.108	0.23
Δ±SD	0.04±0.01	2.84±1.02	3.37±0.895						
p_{adj}^{b}	0.287	0.014*	0.012*						
ES	0.20	1.83	2.00						

a: Calculated by Wilcoxon test with Bonferroni correction

b: Calculated by Mann–Whitney test with Bonferroni correction

* $p_{adj} < 0.017$

According to Table 5, both groups showed a statistically significant improvement in the Knowledge component from the pretest to the posttest ($p_{adj} < 0.017$). However, the effect size for the ML-PhET group (ES = 8.81) was notably higher than that of the control group (ES = 8.00). During the follow-up, between-group comparisons revealed no significant differences, suggesting that the level of Knowledge retention remained stable in both groups over time. Nonetheless, the ML-PhET group clearly excelled in the initial enhancement of conceptual knowledge about solutions.

In the Comprehension component, results indicated a significant difference between the two groups. The ML-PhET group experienced a highly significant increase from pretest to posttest ($p_{adj} = 0.002$), with a very large effect size (ES = 5.33). Comparisons between the groups also showed significant differences in both the posttest and follow-up ($p_{adj} = 0.007$ and 0.009, respectively), indicating that the improvement and retention of conceptual understanding were more pronounced in the experimental group. These findings underscore the effectiveness of the ML-PhET approach in enhancing students' comprehension of solution concepts compared to traditional teaching methods.

In the Application component, the ML-PhET group demonstrated a remarkable improvement from pretest to posttest ($p_{\text{adj}} = 0.001$, ES = 11.15), while the control group showed relatively less progress ($p_{\text{adj}} = 0.010$, ES = 4.85). The between-group differences were significant at both posttest and follow-up ($p_{\text{adj}} = 0.008$ and 0.031, respectively), indicating that learners in the ML-PhET-based learning environment were better equipped to transfer their acquired knowledge about solutions to new and practical contexts.

In the Analysis component, although both groups made progress, the magnitude of improvement in the ML-PhET group ($\Delta = 9.26$, $p_{\text{adj}} = 0.003$) and its effect size (ES = 5.32) were significantly greater than those of the control group. Between group comparisons at both posttest and follow-up were also statistically significant ($p_{\text{adj}} = 0.014$ and 0.012, respectively), demonstrating that the use of PhET simulations within a mobile learning context not only promotes surface-level learning of solution concepts but also enhances higher-order cognitive skills such as analytical thinking.

Figure 2 presents the mean scores of the ML-PhET and control groups across the four cognitive domains of Bloom's taxonomy (Knowledge, Comprehension, Application, and Analysis) related to the concept of solutions, measured at pretest, posttest, and follow-up.

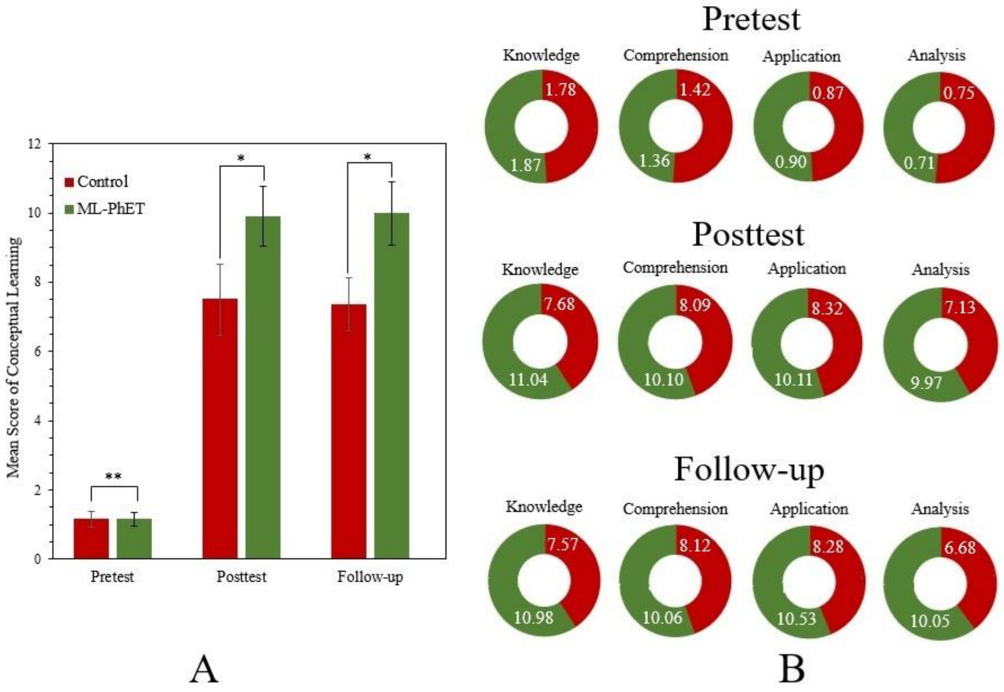

Figure 2- (A) The mean scores of the ML-PhET and control groups across conceptual learning related to the concept of solutions, measured at pretest, posttest, and follow-up ($*p_{adj} < 0.017$, $**p_{adj} > 0.017$). (B) The four cognitive domains of Bloom's taxonomy related to the concept of solutions, measured at pretest, posttest, and follow-up in the ML-PhET and control groups.

According to Figure 2A, a slight difference was noted between the mean scores of the ML-PhET and control groups during the pretest. However, this difference became significantly greater in favor of the ML-PhET group during both the posttest and follow-up ($p_{adj} < 0.017$). The experimental group, which received instruction using the ML-PhET approach, showed a remarkable improvement in learning scores related to the concept of solutions. This improvement was sustained in the follow-up, indicating the long-term stability of the instructional effect. These results confirm the effectiveness of mobile learning environments based on interactive simulations in enhancing conceptual understanding and retention of the concept of solutions over time. Figure 2B presents a detailed analysis of cognitive components across the pretest, posttest, and follow-up. At the pretest, the mean scores for both groups in the Knowledge, Comprehension, Application, and Analysis components of the concept of solutions were nearly identical, demonstrating the initial homogeneity of participants. However, in the posttest, the ML-PhET group exhibited a substantial increase in scores compared to the control group across all components, particularly in Knowledge (11.04 vs. 7.68) and Application (10.11 vs. 8.32), which showed the largest differences. These findings indicate that the ML-PhET approach not only facilitates the transfer of knowledge but also significantly enhances students' ability to apply the concept of solutions in new and practical contexts. During the follow-up, although both groups experienced a slight decrease in scores compared to the posttest, the ML-PhET group continued to outperform the control group. This relative stability suggests that learning the concept of solutions through the ML-PhET approach results in deeper and more enduring learning outcomes compared to traditional instructional methods.

Hypothesis 2: The ML-PhET approach significantly enhances tenth-grade students' creative thinking regarding the concept of solutions.

H0: There is no significant difference in students' creative thinking regarding the concept of solutions when comparing the ML-PhET approach to the traditional teaching method.

H1: There is significant difference in students' creative thinking regarding the concept of solutions when comparing the ML-PhET approach to the traditional teaching method.

Normality of the distributions for creative thinking was examined using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Table 6 shows the obtained data across groups (ML-PhET and control) and time points (pretest, posttest, and follow-up).

Table 6- Normality test for creative thinking variable in ML-PhET and control groups at the pretest, posttest, and follow-up

Group	Test	Kolmogorov-Smirnov		Shapiro-Wilk	
		Statistic	*p*	Statistic	*p*
ML-PhET (N = 126)	Pretest	0.43	0.040*	0.86	0.029*
	Posttest	0.80	0.021*	0.92	0.003*
	Follow-up	0.97	0.035*	0.63	<0.001*
Control (N = 128)	Pretest	0.40	<0.001*	0.76	0.008*
	Posttest	0.32	0.018*	0.89	0.006*
	Follow-up	0.71	0.013*	0.92	<0.001*

*** $p < 0.05$**

Both of Kolmogorov–Smirnov and Shapiro–Wilk tests indicated significant deviations from normality ($p < 0.05$). So, we adopted nonparametric procedures. Table 7 presents the results of within-group and between-group comparisons across the five cognitive domains of Gilford's dimensions related to the concept of solutions among students in the ML-PhET and control groups.

Table 7- Between and within group comparisons of Gilford's dimensions of creative thinking mean scores in ML-PhET and control groups

	Pretest	**Posttest**	**Follow-up**	**Pretest- Posttest**			**Posttest- Follow-up**		
	M±SD	M±SD	M±SD	Δ±SD	p_{adj}^{a}	ES	Δ±SD	p_{adj}^{a}	ES
Fluency									
ML-PhET	57.41±2.27	112.42±4.13	117.52±4.82	55.01±3.13	0.002*	1.35	5.10±4.47	0.438	0.12
Control	59.76±3.48	65.61±2.52	64.43±3.76	5.85±2.93	0.719	0.06	1.18±3.24	0.371	0.02
Δ±SD	2.35±2.80	46.81±3.61	53.09±4.33						
p_{adj}^{b}	0.191	<0.001*	0.003*						
ES	0.07	0.87	0.98						
Flexibility									
ML-PhET	75.08±2.83	79.32±7.37	78.49±10.25	4.24±5.09	0.476	0.06	0.83±0.27	0.639	0.01
Control	72.17±3.22	78.11±5.86	78.67±7.30	5.94±3.64	0.582	0.08	0.56±0.12	0.490	0.01
Δ±SD	2.91±1.07	1.21±0.19	0.18±0.07						
p_{adj}^{b}	0.703	0.124	0.339						
ES	0.04	0.02	0.01						
Originality									
ML-PhET	69.88±2.18	103.41±11.55	102.94±5.81	33.53±9.40	0.001*	0.48	0.47±0.21	0.715	0.01
Control	71.30±1.15	70.89±5.14	69.87±4.07	0.41±0.09	0.077	0.01	1.02±0.73	0.093	0.01
Δ±SD	1.42±0.80	32.52±7.06	33.07±5.34						
p_{adj}^{b}	1.086	0.004*	<0.001*						
ES	0.02	0.47	0.48						
Elaboration									
ML-PhET	81.71±4.65	82.50±8.24	81.83±10.66	0.79±0.55	0.603	0.01	0.67±0.41	0.115	0.01
Control	79.18±6.78	81.07±6.26	79.44±13.57	1.89±0.77	0.511	0.02	1.63±1.00	0.220	0.02
Δ±SD	2.53±0.84	1.43±0.70	2.39±1.04						
p_{adj}^{b}	0.214	0.073	0.081						
ES	0.03	0.02	0.03						
Sensitivity									
ML-PhET	87.38±5.45	108.34±9.30	105.06±12.95	20.96±8.13	0.005*	0.24	3.28±1.16	0.154	0.03
Control	89.01±4.26	86.82±3.71	87.39±9.35	2.19±0.82	0.481	0.02	0.50±0.14	0.083	0.01
Δ±SD	1.63±0.89	21.52±7.08	17.67±5.14						
p_{adj}^{b}	0.553	0.002*	<0.001*						
ES	0.02	0.25	0.20						

a: Calculated by Wilcoxon test with Bonferroni correction

b: Calculated by Mann–Whitney test with Bonferroni correction

* $p_{adj} < 0.017$

According to Table 7, the Fluency component showed that the ML-PhET group experienced a remarkable improvement from pretest to posttest (Δ = 55.01, $p_{adj} = 0.002$, ES = 1.35), while the control group displayed only minimal and statistically insignificant changes ($p_{\text{adj}} = 0.719$). Significant between-group differences were noted at both the posttest and follow-up ($p_{\text{adj}} < 0.001$ and 0.003), underscoring the strong and sustained effectiveness of the ML-PhET approach in enhancing ideational fluency related to the concept of solutions. The large effect size (ES = 0.87–0.98) further supports the effectiveness of mobile learning integrated with interactive simulations in stimulating creativity and expanding divergent thinking among learners.

In the Flexibility component, there were no significant within-group or between-group differences ($p_{\text{adj}} > 0.05$). This suggests that while the ML-PhET approach may provide slight improvements in learners' ability to shift perspectives and adapt cognitively, its impact in this area was weaker than in others. The very small effect size ($\text{ES} \leq 0.06$) indicates that enhancing this aspect of creativity likely requires longer-term interventions or blended instructional approaches to achieve noticeable changes.

For the Originality component, the ML-PhET group demonstrated a highly significant improvement from pretest to posttest ($p_{\text{adj}} = 0.001$, ES = 0.48), while the control group showed negligible change. Significant between-group differences were also found at both the posttest and follow-up ($p_{\text{adj}} = 0.004$ and < 0.001). These results highlight that learning the concept of solutions through the ML-PhET approach effectively fosters the emergence of novel ideas and innovative problem-solving strategies. The moderate to large effect size further confirms the cognitive and motivational dynamism generated by the ML-PhET-based learning environment.

In the Elaboration component, no significant differences were found either within groups or between groups ($p_{\text{adj}} > 0.05$). This indicates that, in the short term, the ML-PhET approach may have limited influence on learners' ability to add detail, expand, or refine ideas. Given the nature of this skill, which requires sustained practice in explaining and elaborating ideas, a more pronounced effect might emerge with longer instructional periods.

Finally, in the Sensitivity component, the ML-PhET group showed a significant improvement from pretest to posttest ($p_{\text{adj}} = 0.005$, ES = 0.24), while no changes were noted in the control group. Significant between-group differences were also observed at both the posttest and follow-up ($p_{\text{adj}} = 0.002$ and < 0.001). This indicates that the ML-PhET approach enhanced learners' ability to identify and analyze complex situations and their awareness and responsiveness to new challenges within the context of the concept of solutions.

Figure 3 presents the mean scores of the ML-PhET and control groups across the five cognitive domains of Gilford's dimensions (Fluency, Flexibility, Originality, Elaboration, and Sensitivity) related to the concept of solutions, measured at pretest, posttest, and follow-up.

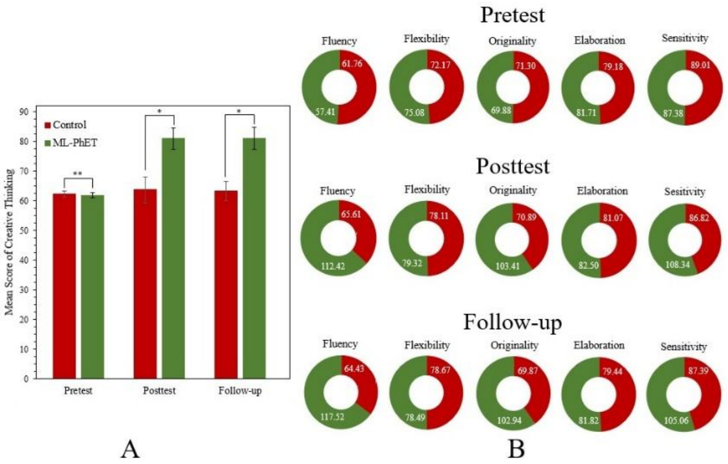

Figure 3- (A) The mean scores of the ML-PhET and control groups across creative thinking related to the concept of solutions, measured at pretest, posttest, and follow-up (*$p_{adj} < 0.017$, **$p_{adj} > 0.017$). (B) The five cognitive domains of Gilford's dimensions related to the concept of solutions, measured at pretest, posttest, and follow-up in the ML-PhET and control groups.

According to Figure 3A, the ML-PhET group achieved a significantly higher mean overall score in creative thinking than the control group during both the posttest and follow-up ($p_{\text{adj}} < 0.017$). In contrast, the difference between the two groups in the pretest was minimal and statistically insignificant ($p_{\text{adj}} > 0.017$). This suggests that the ML-PhET approach effectively enhanced students' creative thinking abilities, with this positive effect enduring into the follow-up, reflecting the long-term stability of the instructional impact. Figure 3B illustrates that the mean differences in creative thinking components between the two groups were negligible in the pretest, indicating the initial homogeneity of participants. However, in the posttest, the ML-PhET group demonstrated significant improvements in Fluency, Originality, and Sensitivity compared to the control group, while no significant changes were noted in Flexibility and Elaboration. This trend continued into the follow-up, where, despite a slight decrease in scores, the ML-PhET group consistently outperformed the control group across all components. These findings indicate that the ML-PhET approach effectively enhances key aspects of creative thinking particularly idea generation and problem sensitivity among students.

Discussion

The purpose of this study was to investigate the impact of the ML-PhET approach on understanding the concept of solutions and fostering creative thinking among tenth-grade students. The results indicated a significant increase in the mean learning scores of students in the ML-PhET group across all cognitive domains of Bloom's taxonomy, with these improvements being retained for at least 60 days. However, the mean creative thinking scores for ML-PhET group did not show similar increases across all components of Guilford's model of creativity. Analysis of the ML-PhET approach revealed a positive and lasting impact on students' comprehension of the concept of solutions, demonstrating its effectiveness in enhancing all levels of cognitive learning. The large and statistically significant effect sizes observed in the ML-PhET group illustrate the approach's potential to deepen learning and promote higher-order cognitive processes. These findings suggest that the ML-PhET approach can effectively replace or complement traditional teaching methods for this concept. By enabling students to engage in virtual experiments via their mobile devices, they can explore abstract concepts interactively and apply theoretical knowledge in practical situations. In this context, Penelitian et al. (2023) highlighted that the PhET interactive simulation offers a visual and interactive learning environment that supports problem-based learning effectively. Similarly, Ndagijimana et al. (2025) found that utilizing the PhET interactive simulator significantly enhances students' learning processes and improves their grasp of fundamental concepts related to chemical equations, acids, bases, and pH. However, a key difference between the studies is that the improvement in the Comprehension component was approximately 15% greater in Ndagijimana et al. (2025) than in the current study. This discrepancy may be due to the higher levels of physical and social interaction between teachers and students, as well as the combined use of active learning and the PhET interactive simulation in that study, factors likely contributing to enhanced learning quality and deeper conceptual understanding. In another relevant study, Salame and Makki (2021) demonstrated that the PhET interactive simulator serves as a subtle yet effective tool for supporting learning during experimentation, facilitating guided inquiry learning without overloading students cognitively. The primary strength of the present study, compared to previous research, is its experimental design, which allowed for the independent assessment of the role of PhET interactive simulations within the mobile learning module. This differentiation was not present in earlier studies. Despite this methodological advancement, the findings of the present research, along with prior studies, provide a more comprehensive understanding of the benefits of integrating mobile learning environments utilizing simulations like PhET with other instructional strategies, such as active learning and guided inquiry. This integration can lead to enhanced learning quality and an improved educational experience for students. The findings of this study support a significant body of prior research on the effectiveness of educational simulations in enhancing student learning. However, some studies, such as those by Lamb et al. (2018) and Elendu et al. (2024), have reported differing results. These studies found that certain educational simulations had minimal impact on students' understanding of specific concepts. This limitation is often attributed to poorly designed interactive activities, short intervention durations, or a misalignment between learning objectives and the nature of the simulation tool used. These inconsistencies suggest that the effectiveness of simulations is not solely dependent on the tool itself; it primarily relies on the quality of instructional design, the facilitation of learning activities, and the level of active engagement from learners.

The findings of this study suggest that using the PhET interactive simulation in a mobile learning environment significantly enhances key dimensions of creative thinking, particularly Fluency, Originality, and Sensitivity in understanding the concept of solutions. However, its impact on Flexibility and Elaboration was less pronounced. Strengthening the Flexibility and Elaboration aspects of students' creative thinking appears to require open-ended, problem-oriented activities related to the concept of solutions, activities that enable shifting perspectives, adding details, and expanding initial ideas. Thus, the ML-PhET approach may not have fully provided these conditions due to its structured design and limited incorporation of open-ended tasks without predetermined outcomes, which could explain its reduced effectiveness in fostering these two components of creative thinking. The present study emphasizes that the ML-PhET approach positively influences both the cognitive aspects of learning and the generative processes of creativity in the context of the concept of solutions, indicating its potential as an effective tool for cultivating creative thinking in educational settings. Consistent with these findings, Alt et al. (2023) reported that mobile simulation-based learning enhances fluency, originality, and problem-solving skills among students, though it does not lead to significant improvements in flexibility. Similarly, Yasin and Yunus (2014) found that students using educational simulation software performed significantly better in problem-solving tasks compared to those who received only traditional lecture-based and laboratory-based instruction. Furthermore, Chernikova et al. (2020) attributed the effectiveness of simulations in developing higher-order thinking skills and improving students' cognitive abilities to their ability to provide authentic learning experiences. These experiences allow learners to practice complex skills in controlled yet realistic environments that reflect real-world challenges. Such environments promote competencies such as idea generation, innovation, and problem solving, facilitating learning that goes beyond mere knowledge reproduction. Overall, the alignment of the present findings with previous studies supports the conclusion that integrating laboratory simulations into teaching, especially within interactive and mobile learning contexts, is crucial for reinforcing the components of fluency, originality, and problem solving. This effect can be attributed to the active and engaging nature of simulation-based environments, which encourage students to participate actively in creative thinking, hypothesis formulation, and problem solving, transforming them from passive recipients of information into active agents in constructing and expanding their own knowledge. In contrast to the findings of this study, Simanjuntak et al. (2021) reported different results, stating that educational simulations do not significantly impact students' creativity. This discrepancy suggests that simply using simulations and mobile learning is not enough to enhance students' creative thinking. Instead, improving creativity likely requires more comprehensive learning activities and opportunities for reinterpreting problems.

Based on the findings of this study, the ML-PhET approach may serve as a valuable supplementary resource within chemistry education, provided that its implementation aligns with school policies, available infrastructure, and learners' equitable access to digital tools. This integration aims to enhance higher-order cognitive skills such as analysis, evaluation, creation, and creative thinking among students. The recommendation is firmly rooted in the study's results, which showed that implementing the ML-PhET approach resulted in a significant and sustained increase in learning scores across Bloom's cognitive domains and Guilford's creativity components, with these effects remaining stable over time after the intervention. By adopting this policy, we expect to promote the understanding of abstract scientific concepts through visual and interactive experiences, leading to improved academic performance, increased learning motivation, and better preparation of students for future educational and professional opportunities in STEM disciplines. Additionally, this approach has the potential to promote equitable access to high-quality education for underserved or disadvantaged regions, thereby helping to reduce educational and gender disparities. However, challenges related to implementation, such as insufficient digital infrastructure, limited access to mobile devices, and resistance to change, must be addressed through careful planning, government financial support, and collaboration between the Ministry of Education and the Ministry of Communications and Information Technology. In summary, the integration of ML-PhET, when implemented selectively and within appropriate pedagogical frameworks, has the potential to enhance instructional quality; however, its applicability depends on contextual factors such as institutional regulations, classroom management considerations, and students' access to ML-based technologies.

Limitations and Suggestions

The present study offers valuable insights into the effects of the ML-PhET approach on students' learning and the development of creative thinking regarding the concept of solutions, but it has notable limitations. Firstly, the statistical population was confined to female tenth-grade students, which limits the generalizability of the findings. Secondly, intervening variables, such as students' prior familiarity with technology and individual differences in learning styles, were not adequately controlled. Thirdly, the instrument used to assess creativity, a researcher-developed questionnaire, may have introduced response bias. To address these limitations, future studies should include more diverse samples from different grade levels, integrate individual variables into the research design, and utilize multiple assessment tools (such as performance-based tests and qualitative analyses of students' learning activities) alongside questionnaires. Another limitation of this study is that the implementation of the ML-PhET approach relies on sufficient access to digital devices, which varies across schools and among students. Additionally, some schools impose restrictions on mobile phone usage, complicating the application of these interventions. Consequently, the findings of this study should be interpreted within this context of constraints. Effective implementation of the approach requires appropriate infrastructure and adequate instructional supervision. It is recommended that teachers use the ML-PhET approach in settings like laboratories or smart classrooms, ensuring that it is conducted under supervision and aligned with clearly defined educational objectives. Furthermore, the Ministry of Education should develop strategies to address digital access challenges by providing necessary infrastructure and regulating the use of smart devices effectively. The findings of this study pave the way for future research. Subsequent studies should explore the effect of the ML-PhET approach in conjunction with other active learning strategies, like project-based learning or collaborative learning, to gain a more comprehensive understanding of its impact on cultivating creative thinking. Additionally, investigating the long-term sustainability of this instructional approach over extended periods could provide clearer insights into the durability of learning and creativity outcomes among students. Furthermore, future research should adopt a comparative approach to analyze differences across various scientific disciplines (e.g., physics, chemistry, biology, and mathematics) to clarify the applicability and effectiveness of the ML-PhET approach across different STEM domains. Conducting qualitative studies could also yield deeper insights into students lived experiences during the learning process within the ML-PhET approach.

Conclusion and Recommendations

This study aimed to investigate the impact of the ML-PhET approach on learning and the development of creative thinking among tenth-grade students regarding the concept of solutions. The findings indicated that this approach significantly enhanced students' understanding of the concept of solutions across various levels of Bloom's cognitive domain, including Knowledge, Comprehension, Application, and Analysis. The large and statistically significant effect sizes observed in the ML-PhET group demonstrate the effectiveness of this approach in deepening conceptual understanding and promoting higher-order cognitive processes. These results confirm that the ML-PhET approach can serve as an effective alternative or complement to traditional instructional methods in teaching the concept of solutions. Additionally, the findings revealed substantial improvements in certain components of creative thinking, such as Fluency, Originality, and Sensitivity, within the experimental group, while no significant changes were observed in the components of Flexibility and Elaboration. This emphasizes that the ML-PhET approach positively influences not only cognitive aspects of learning but also the generative processes of creativity, suggesting its potential as an effective tool for fostering creative thinking in educational contexts. In conclusion, while the ML-PhET approach effectively strengthens conceptual learning and enhances specific dimensions of creativity, it is not sufficient on its own to address all aspects of creative thinking and therefore requires integration with other instructional strategies. Overall, the results suggest that the ML-PhET approach can be a valuable complement to traditional methods of chemistry instruction, significantly enhancing the quality of students' learning by providing a dynamic and authentic learning environment. This study not only contributes to the scientific literature on chemistry education and the broader STEM fields but also serves as a practical guide for teachers, instructional designers, and policymakers seeking to integrate interactive technologies and mobile learning into curricula to foster a creative and competent generation of learners.

Conflict of Interest

The authors have declared no conflicts of interest.

Acknowledgments

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References

Akgün, A. (2009). The Relation between Science Student Teachers' Misconceptions about Solution, Dissolution, Diffusion and their Attitudes toward Science with their Achievement. *Education and Science*, *34(154),* 26-36. https://educationandscience.ted.org.tr/article/view/835

Akrami, Z. & Shirvani, M. (2025). Deaf and hard-of-hearing students' chemistry learning and engagement: Smartphone-created multimodal artifacts, *Journal of Chemical Education, 102,* 5218-5228. https://doi.org/10.1021/acs.jchemed.5c01424

Akrami, Z. (2022). The effectiveness of education with the STEM approach in the development of entrepreneurial thinking in chemistry students. *Chemistry Education Research and Practice, 23(2),* 475-485. https://doi.org/10.1039/D2RP00011C

Akrami, Z.; Amani, V.; Bavardi, J. (2025). Identifying key components and objectives of mobile learning in chemistry education. *Journal of Science Education Technology, 34,* 367–383; https://doi.org/10.1007/s10956-024-10196-8

Aliyu, H. (2025). A review of instructional strategies for maximizing the effectiveness of PhET interactive simulations in chemistry education. *Rima International Journal of Education, 4(1),* 479-487.

Alt, D., Naamati-Schneider, L., & Weishut, D.J. (2023). Competency-based learning and formative assessment feedback as precursors of college students' soft skills acquisition. Studies in Higher Education, 48, 1901 - 1917. https://doi.org/10.1080/03075079.2023.2217203

Alwafi, E. M. (2025). The impact of AI-assisted peer review on students' AI-feedback literacy, motivation and self-esteem: Integrating experiential learning and self-determination theory, *Learning and Motivation, 92,* 102215. https://doi.org/10.1016/j.lmot.2025.102215

Azamat, J. (2023). The role of research and innovation in developing chemistry education. *Research in Chemistry Education, 5(3),* 1-2. https://doi.org/10.48310/chemedu.2023.3197

Buhera, R., Ayu, S. B., & Nurohman, S. (2024). Enhancing students' science process skills through design worksheet-based inquiry integrated PhET simulation on acid and base material. *Journal IPA & Pembelajaran IPA, 8(3),* 267-285. https://doi.org/10.24815/jipi.v8i3.39762

Chernikova, O., Heitzmann, N., Stadler, M., Holzberger, D., Seidel, T., & Fischer, F. (2020). Simulation-based learning in higher education: A meta-analysis. *Review of Educational Research*, 90, 499 - 541. https://doi.org/10.3102/0034654320933544

Clark, T. M. (2024). Using multiple PhET sims to investigate greenhouse gases within a real-world context. *Journal of Chemical Education, 101(10),* 4242-4250. https://doi.org/10.1021/acs.jchemed.4c00551

Clark, T. M., & Chamberlain, J. M. (2014). Use of a PhET interactive simulation in general chemistry laboratory: Models of the hydrogen atom. *Journal of Chemical Education, 91(8),* 1198-1202. https://doi.org/10.1021/ed400454p

Cronbach, L. J. & Shavelson, R. J. (2004). My current thoughts on coefficient alpha and successor procedures. *Educational and Psychological Measurement. 64(3),* 391–418; https://doi.org/10.1177/0013164404266386

Diab, H., Daher, W., Rayan, B., Issa, N., & Rayan, A. (2024). Transforming science education in elementary schools: The power of phet simulations in enhancing student learning. *Multimodal Technologies and Interaction, 8(11),* 105-121. https://doi.org/10.3390/mti8110105

Doronina, N., Lazorenko, L., & Andriichuk, T. (2024). Enhancing the practical learning of english: Applying Bloom's Taxonomy to the ESP curriculum for students of higher education institutions. *Economics & Education*, *9(3),* 15-20. https://doi.org/10.30525/2500-946X/2024-3-2

Elendu, C., Amaechi, D.C., Okatta, A.U., Amaechi, E.C., Elendu, T.C., Ezeh, C.P., & Elendu, I.D. (2024). The impact of simulation-based training in medical education: A review. *Medicine*, *103*(27), e38813. https://doi.org/10.1097/MD.0000000000038813

Fadillah, M. A., Hirahmah, A., & Fitri, N. C. (2025). Mobile learning media and physics education: Exploring student preferences, competence, and motivation in the digital era. *Advances in Mobile Learning Educational Research, 5(2),* 1437-1448. https://doi.org/10.25082/AMLER.2025.02.002

Guilford, J. P. (1950). Creativity. American Psychologist, 5, 444-454.

Hurst, G. A., Quiroz-Martínez, D., & Wissinger, J. E. (2025). Chemistry education for climate empowerment and action. *Journal of Chemical Education, 102(4),* 1349-1351. https://doi.org/10.1021/acs.jchemed.5c00306

Kang, H. (2021). Sample size determination and power analysis using the G* Power software. *Journal of educational evaluation for health professions, 18,* 1149215. https://doi.org/10.3352/jeehp.2021.18.17

Kizito, I. G., & Hassan, S. (2024). PhET interactive simulations as an effective tool for teaching chemistry: A review. *International Journal of Innovative Social & Science Education Research, 12(2),* 166-169. https://doi.org/10.1021/ed4005084

Kizito, I.G., & Hassan, S. (2024). PhET interactive simulations as an effective tool for teaching chemistry: A review. *International Journal of Innovative Social & Science Education Research 12(2)*, 166-169.

Krathwohl, D.R. (2002). A Revision of Bloom's Taxonomy: An Overview. *Theory Into Practice, 41(4),* 212–218. https://doi.org/10.1207/S15430421TIP4104_2

Lamb, R.L., Annetta, L., Firestone, J., & Etopio, E. (2018). A meta-analysis with examination of moderators of student cognition, affect, and learning outcomes while using serious educational games, serious games, and simulations. *Computers in Human Behaviour*, *80*, 158-167. https://doi.org/10.1016/j.chb.2017.10.040

Levin, R. L.; Rubin, D. S.; Siddiqui, M. H. & Rastogi, S. Statistics for Management, 8nd ed.; Pearson: India. 2017.

Maesaroh, N., & Sutikno, P. Y. (2025). Effectiveness of the PhET simulation assisted by songs to improve students critical thinking skills in electrical circuits. *Journal Pijar Mipa, 20(2),* 356-364. https://doi.org/10.29303/jpm.v20i2.8729

Moore, E. B., Chamberlain, J. M., Parson, R., & Perkins, K. K. (2014). PhET interactive simulations: Transformative tools for teaching chemistry. *Journal of chemical education, 91(8),* 1191-1197. https://doi.org/10.1021/ed4005084

Moradi, R., & Arasteh Saleh Kohi, M. (2023). Enriching the learning environment based on mobile technologies and investigating its impact on students' learning and academic engagement in chemistry. *New Educational Approaches*, *18*(1), 47-66. https://doi.org/10.22108/nea.2023.136616.1868

Ndagijimana, J. B., Musengimana, J., Mushimiyimana, H., Mukama, E., Habimana, O., Manirakiza, P., ... & Lakin, E. (2025). Contribution of an instructional module incorporating PhET simulations to Rwandan students' knowledge of chemical reactions, acids, and bases through social interactions. *Chemistry Education Research and Practice, 26(1),* 289-299. https://doi.org/10.1039/D4RP00105B

Nuraida, O., Akbar, G. S., Farida, I., & Rahmatullah, S. (2021). Using PhET simulation to learning the concept of acid-base. Journal of Physics: Conference Series, 1869(1), 012020. https://doi.org/10.1088/1742-6596/1869/1/012020

Penelitian, J.H., Pendidikan, P., Samitra, D., Firdaus, M.L., & Krisnawati, Y.K. (2023). Physics education technology project (PhET): Interactive simulation to improve students' understanding of concepts and perceptions. *Journal Pedagogy. 10(3),* 646-654. https://doi.org/10.33394/jp.v10i3.7879

Salame, I. I., & Makki, J. (2021). Examining the use of PhET simulations on students' attitudes and learning in general chemistry II. *Interdisciplinary Journal of Environmental and Science Education, 17(4),* e2247. https://doi.org/10.21601/ijese/10966

Sayaf, A.M. (2023). Adoption of E-learning systems: An integration of ISSM and constructivism theories in higher education, *Heliyon, 9,* e13014. https://doi.org/10.1016/j.heliyon.2023.e13014

Sequeira, C. A. & Borges, E. M. (2024). Enhancing statistical education in chemistry and STEAM using JAMOVI. Part 2. Comparing dependent groups and principal component analysis (PCA). *Journal of Chemical Educucation, 101(11),* 5040–5049; https://doi.org/10.1021/acs.jchemed.4c00342

Sharifati S., Nili Ahmad Abadi M.R. & Maghami H. (2021). The effect of simulation chemistry training on spatial ability and problem-solving skills for tenth year female students in Tehran. *Education Strategy Medicine Science*, *14 (2),* 28-38. http://edcbmj.ir/article-1-2396-fa.html

Sharifzadeh, F., & Ahmadabadi, Z. (2025). Improving the learning of subatomic structures through the use of technology and educational-participatory games for first period of high school students. Research in Chemistry Education, https://doi.org/10.48310/chemedu.2025.18115.1301

Sharifzadeh, F., & Ahmadabadi, Z. (2025). Improving the learning of subatomic structures through the use of technology and educational-participatory games for junior high school students. *Research in Chemistry Education,* 49-66. https://doi.org/10.48310/chemedu.2025.18115.1301

Simanjuntak, M.P., Hutahaean, J., Marpaung, N., & Ramadhani, D. (2021). Effectiveness of problem-based learning combined with computer simulation on students' problem-solving and creative thinking skills. *International Journal of Instruction*, *14(3),* 519-534. https://doi.org/10.29333/iji.2021.14330a

Siswanto, D. A. C., Iswanto, B. H., & Rahmawati, Y. (2025). The impact of mobile learning on physics education: A systematic literature review. *Journal Penelitian & Pengembangan Pendidikan Fisika, 11(1),* 13-26. https://doi.org/10.21009/1.11102

Suparman, A.R., Rohaeti, E., & Wening, S. (2024). Student misconception in chemistry: A systematic literature review. *Pegem Journal of Education and Instruction*, *14(2),* 238-252. https://doi.org/10.47750/pegegog.14.02.28

Talanquer, V. (2022). The complexity of reasoning about and with chemical representations. *Journal of the American Chemical Society, 2(12),* 2658-2669. https://doi.org/10.1021/jacsau.2c00498

Yasin, R.M., & Yunus, N. (2014). A meta-analysis study on the effectiveness of creativity approaches in technology and engineering education. *Asian Social Science, 10,* 242-252. https://doi.org/10.5539/ASS.V10N3P242