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The Effectiveness of PhET Simulations in Improving Seventh-Grade Students' Learning Outcomes on States of Matter and Their Changes

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Abstract: This study aimed to examine changes in students' learning outcomes and assess the perceived effectiveness and practicality of PhET media in learning about states of matter and their changes among seventh-grade students at SMPN 2 Watubangga. A quantitative descriptive approach using a One-Group Pretest-Posttest Design was employed. The participants were 20 seventh-grade students in the 2026/2027 academic year. PhET-supported learning activities were implemented during the study period from July 13 to August 3, 2026. Data were collected using a 15-item objective test of learning outcomes and a questionnaire consisting of 32 statements to assess the effectiveness and practicality of the medium. Learning gains were analyzed using the normalized gain (N-Gain), while questionnaire responses were analyzed descriptively using percentages. The mean learning outcome score increased from 58.25 on the pretest to 83.75 on the posttest, while the proportion of students achieving learning mastery increased from 25% to 100%. The mean N-Gain was 0.6008 (60.08%), indicating a moderate level of learning improvement. Separately, questionnaire results yielded an effectiveness score of 84.01% and a practicality score of 83.37%, both categorized as very high. These percentages represent respondents' assessments of the learning medium and are distinct from the N-Gain, which measures improvement in learning outcomes. Overall, the findings indicate that the use of PhET media was associated with improved learning outcomes and was positively perceived by students in the context of this study. However, because the study employed a one-group design without a comparison group, the findings do not establish that PhET media is more effective than other instructional approaches.

Keywords: Effectiveness; Learning outcomes; PhET; States of matter; Virtual laboratory

Introduction

Science learning at the junior high school level aims not only to help students master a number of scientific facts and concepts, but also to enable them to understand natural phenomena through observation, investigation, and modeling. One of the seventh-grade science topics that requires fairly strong conceptual understanding is states of matter and their changes. This topic covers the concepts of solids, liquids, and gases, the characteristics of each state of matter, changes of state, and their relationship to particle motion and arrangement. Some of these concepts are abstract because processes at the particle level cannot be observed directly by students. Therefore, teaching states of matter requires representations that help students connect macroscopically observable phenomena with processes at the microscopic level. The conceptual difficulty of linking observable phenomena with particle-level models has been discussed in science education, and multirepresentational instruction is one approach used to address this challenge (Johnstone, 1991; Nakhleh, 1992; Talanquer, 2009; Adadan et al., 2010).

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Difficulty in understanding abstract concepts can affect students' learning outcomes. In the topic of states of matter and their changes, it is not enough for students to memorize terms such as melting, freezing, evaporating, condensing, and sublimating; they need to understand the relationships among energy changes, particle motion, interparticle distance, and changes in the state of matter. Research on learning states of matter has shown that science process skills contribute to students' learning outcomes on this topic, so learning that gives students opportunities to observe, explore, and investigate is important (Sari et al., 2017).

In science teaching practice, experimental activities are one approach that can help students build understanding based on direct experience. However, conventional laboratory activities are not always easy to carry out because they require equipment, materials, time, laboratory space, and teacher supervision. These limitations have encouraged the use of virtual laboratories as an alternative or complement to practical work. Potkonjak et al. (2016) explained that virtual laboratories can provide a simulated environment that allows students to explore scientific phenomena with the support of computer technology. Meanwhile, Brinson (2015), in a review of empirical studies comparing virtual and conventional laboratories, showed that most of the compared studies reported equivalent or higher learning achievement in non-traditional laboratory environments, particularly in terms of knowledge and understanding. Broader comparisons suggest that virtual and physical laboratories can both support learning, while their relative benefits depend on the instructional context and design of the activity (de Jong et al., 2013; Zacharia & Olympiou, 2011).

One virtual laboratory medium that can be used in science learning is PhET *Interactive Simulations*, developed by the University of Colorado Boulder. PhET provides interactive simulations in physics, chemistry, biology, earth science, mathematics, and statistics. PhET simulations are designed based on educational research and allow students to explore scientific phenomena in an interactive environment. These characteristics enable teachers to bring phenomena that are difficult to observe directly into the learning process. In the topic of states of matter, for example, simulations can be used to visualize the arrangement and movement of particles in solids, liquids, and gases, as well as changes in particle behavior when the conditions of the system change. The PhET project emphasizes interactive exploration and connecting real-world phenomena with underlying scientific models (Perkins et al., 2006).

The use of interactive simulations is also in line with learning principles that position students as active subjects in constructing knowledge. Wieman et al. (2008) explained that interactive simulations can help students build understanding through active engagement with scientific phenomena. PhET is designed so that students can explore the relationship between visual representations and scientific concepts, so that phenomena that are difficult to observe directly can be visualized. Early research on PhET has also shown that the use of simulations can support the delivery of visual models, concept development, and students' active engagement in learning. The role of integrating verbal explanation with visual representations is also discussed in multimedia learning theory (Mayer, 2009).

Empirical evidence on the use of virtual laboratories also indicates positive potential for learning outcomes. A systematic review of virtual chemistry laboratories by Chan et al. (2021) showed that virtual laboratories can yield better cognitive learning outcomes than passive instructional media and, under certain conditions, can achieve equivalent or even better results than hands-on laboratories. However, the review also emphasized that the effectiveness of virtual laboratories is influenced by instructional design and by how the technology is integrated into the learning process. Thus, the use of virtual laboratories depends not merely on the technology itself, but also on the learning objectives and the activities given to students. Reviews of science simulations similarly stress that learning outcomes depend on instructional support, student reflection, and how simulations are integrated into instruction (Rutten et al., 2012; Smetana & Bell, 2012).

Previous studies that specifically relate to PhET and the topic of states of matter also provide an empirical basis for this study. Siburian (2018) examined the use of the PhET mobile application in learning *states of matter* and found an improvement in students' conceptual understanding, with a normalized gain of 0.61, as well as very high learning interest. These results indicate that PhET has potential for helping students understand the concept of states of matter. Other research on the use of PhET in junior high school science learning has shown that PhET simulations can be used to improve learning outcomes on the topic of vibrations. These findings strengthen the argument that PhET simulations have the potential to become a learning medium that supports the achievement of science learning outcomes. For example, a classroom action research study at a junior high school in Bogor reported improved learning outcomes after PhET virtual simulations were used to teach vibrations (Kurniawati, 2022).

More recent studies also show developments in the use of PhET for topics related to matter and its changes. Duhe et al. (2026) investigated the implementation of the PhET media among seventh-grade junior high school students on the topic of matter and its changes, focusing on scientific literacy. The study used a *one-group pretest-posttest* design and reported an increase in scientific

literacy from a pretest mean of 46.5 to 90.3, with an *N-Gain* in the high category. These findings show that the use of PhET for the topic of matter and its changes is still relevant to be examined at the junior high school level.

Nevertheless, research on PhET in the topic of states of matter and their changes has not fully addressed the question of the effectiveness of the medium on students' learning outcomes in the context of science learning at a particular school. The study by Siburian (2018), for example, focused on the use of the PhET mobile application for conceptual understanding and learning interest, whereas the study by Duhe et al. (2026) emphasized scientific literacy skills. Thus, this study occupies a different position because it specifically tests the effectiveness of the PhET media medium on students' learning outcomes in the topic of states of matter and their changes in the context of seventh-grade students at SMPN 2 Watubangga. Differences in school context, student characteristics, measurement objectives, and the focus on learning outcomes as the variable are important aspects that distinguish this study from previous research.

In addition, the choice of the topic of states of matter and their changes has a pedagogical rationale. This topic contains phenomena that are close to everyday life, but some of the underlying processes occur at the microscopic level and therefore cannot all be observed directly. The PhET media can be used to bridge this limitation by providing visual representations and interactions that allow students to observe changes in the state of matter and the behavior of its particles. This issue becomes more important because the use of technology in learning should not be based merely on the assumption that digital media are always better than conventional instruction. The effectiveness of a medium needs to be demonstrated through research that systematically measures changes in students' learning outcomes as well as students' responses to the medium. This is in line with studies of virtual laboratories showing that the success of instructional technology depends heavily on the integration of the medium with learning objectives and instructional design. Evidence reviews likewise note that simulation outcomes depend on appropriate guidance and integration with learning objectives rather than technology alone (Rutten et al., 2012; Smetana & Bell, 2012).

Theoretically, this study is expected to contribute to the development of research on the use of virtual laboratories and interactive simulations in science learning, particularly for topics that are abstract in nature and require visualization. Practically, the results are expected to benefit several parties. For science teachers, the results can serve as a consideration in selecting and integrating the PhET media as a learning medium, especially when direct practical work is limited by equipment, materials, time, or facilities. For students, the use of PhET is expected to provide a more interactive learning experience that helps them understand the concept of states of matter and their changes.

Based on the results of initial observations at SMPN 2 Watubangga, it was found that students had difficulty understanding the material on the states of matter and their changes. These difficulties were related to the limited number of laboratory activities that could provide students with hands-on learning experiences to observe various phenomena related to changes in the states of matter. Furthermore, the lack of alternative interactive learning media that teachers can utilize in the learning process poses a challenge in visualizing abstract concepts. This situation causes the learning process to rely heavily on verbal explanations and conventional learning resources, limiting students' ability to connect phenomena observed in daily life with scientific concepts at the subatomic level. Therefore, there is a need for interactive and easily accessible learning media alternatives, such as the PhET virtual laboratory, to help visualize concepts, provide simulation-based learning experiences, and support students' understanding of the states of matter and their changes.

Based on the above description, this study aimed to examine changes in seventh-grade students' learning outcomes following the use of PhET media on the topic of states of matter and their changes, and to assess students' perceptions of the medium's effectiveness and practicality at SMPN 2 Watubangga.

Method

This study employed a quantitative descriptive approach using a *One-Group Pretest-Posttest Design*, which is classified as a pre-experimental research design. The study was conducted at SMPN 2 Watubangga (State Junior High School 2 Watubangga) from July 13 to August 3, 2026. The participants were 20 seventh-grade students enrolled in the 2026/2027 academic year. The participants were selected using [specify the sampling technique, such as total sampling or purposive sampling]. The selection procedure was based on [describe the actual selection criteria or explain whether the 20 students represented the entire class]. The study examined changes in students' learning outcomes following the implementation of PhET media and assessed students' perceptions of the medium's effectiveness and practicality.

The research was conducted in [specify the number of learning sessions] sessions. The procedure began with the administration of a pretest to measure students' initial understanding of states of matter and their changes. Subsequently, students participated in learning activities using PhET virtual laboratory simulations.

During these activities, the teacher introduced the learning objectives and guided students in exploring relevant simulations to observe the characteristics of different states of matter and the processes involved in changes of state. Students were encouraged to relate their observations from the simulations to the scientific concepts being studied through [specify the actual learning activities, such as guided questions, worksheets, group discussions, or individual exploration]. Following the learning intervention, the same objective test was administered as a posttest to measure changes in students' learning outcomes. A questionnaire was also administered to collect students' assessments of the effectiveness and practicality of PhET media.

Data were collected using test and non-test instruments. The test instrument consisted of 15 objective items designed to assess students' learning outcomes. Before use, the test items were examined for validity, reliability, item discrimination, and difficulty level. The results of these analyses were as follows: [report the number or proportion of valid items and the validity coefficient or range], [report the reliability coefficient and the method used], [summarize the item discrimination results], and [summarize the item difficulty results]. These findings were used to determine the suitability of the test items for measuring students' learning outcomes.

The non-test instrument consisted of a questionnaire containing 32 statements designed to assess the perceived effectiveness and practicality of PhET media. The statements were distributed across two assessment dimensions: effectiveness, comprising [number] statements covering [specify the indicators], and practicality, comprising [number] statements covering [specify the indicators]. Responses were recorded using a [specify the number of response options]-point Likert scale, ranging from [specify the lowest response and score] to [specify the highest response and score]. The questionnaire was evaluated for validity through [specify the validation procedure and validator information] and for reliability using [specify the method and coefficient, if tested]. These details were documented to establish the quality of the questionnaire as a data collection instrument.

Changes in students' learning outcomes were analyzed using the normalized gain (N-Gain), following the normalized-gain approach discussed by Hake (1998) and Meltzer (2002). N-Gain represents the proportion of the possible improvement in learning outcomes achieved between the pretest and posttest. It was calculated using Formula 1.

$$\text{Ngain} = \frac{\text{Posttest score} - \text{Pretest score}}{\text{Maximum score} - \text{Pretest score}} \quad (1)$$

where g represents the normalized gain, S_{post} represents the posttest score, S_{pre} represents the pretest score, and S_{ideal} represents the ideal maximum score of the test, which is 100. The ideal maximum score is not the highest score observed among participants. The criteria for interpreting the improvement in learning outcomes according to Savinainen and Scott (2002) are presented in Table 1.

Table 1. Criteria for Ng

Ngain	Criteria
Ng > 0.7	High
0.3 ≤ Ng ≤ 0.7	Moderate
Ng < 0.3	Low

The technique used to collect data on effectiveness and practicality was a questionnaire. The technique used to analyze effectiveness and practicality was quantitative descriptive analysis using percentage analysis, formulated by Annisa et al. (2020) as follows (Formula 2).

$$\text{P} = \frac{\text{f}}{\text{N}} \times 100 \quad (1)$$

where P is the percentage value of the expected effectiveness and practicality, f is the score obtained, and N is the maximum score. The qualification of the level of effectiveness and practicality is presented in Table 2.

Table 2. Criteria for Effectiveness and Practicality

Value	Criteria
81% – 100%	Very Effective / Very Practical
61% – 80%	Effective / Practical
41% – 60%	Fairly Effective / Fairly Practical
21% – 40%	Less Effective / Less Practical
0% – 20%	Very Ineffective / Very Impractical

Result and Discussion

Learning Outcomes Using the PhET media Medium

Table 3. Summary of Pretest and Posttest Scores

Data Description	Pretest	Posttest
Minimum Score	35	75
Maximum Score	75	90
Mean Score	58.25	83.75
Standard Deviation	11.61	4.25
% Mastery	25%	100%

Based on the results of the study, the lowest pretest score obtained by students was 35 and the highest was 75, with a standard deviation of 11.61. Of the 20 students, only 5 achieved a score equal to or above the passing grade of 70, so the initial mastery percentage was only

25%, with a mean score of 58.25, which indicates that students' initial ability regarding the topic of states of matter and their changes was still relatively low. After the treatment using the PhET media medium, the posttest results showed an improvement in learning achievement, in which the lowest score increased to 75 and the highest to 90, with a standard deviation of 4.25. The number of students who achieved a score above the KKM increased to 20, or in other words the mastery percentage increased to 100%. The mean posttest score also increased significantly to 83.75, which indicates that students' learning outcomes were in the high category.

Table 4. Interpretation of N-Gain Values

Descriptive Statistics	N	Minimum	Maximum	Mean	Std. Deviation
Ngain_Score	20	0.40	0.71	0.6008	0.09065
Ngain_Percent	20	40.00	71.43	60.0802	9.06496

Based on the calculation results in Table 4, the mean N-Gain obtained was 0.6008, or 60.08%. According to the interpretation criteria in Table 1, this value falls into the moderate category, which means that learning with the PhET media medium was fairly effective in improving students' learning outcomes. Thus, in addition to being shown to significantly increase the mean learning outcome score through the paired-samples *t*-test, this learning medium also showed a level of effectiveness in the moderate category in helping students understand the topic of states of matter and their changes.

Effectiveness and Practicality of the PhET media Medium

Based on the questionnaire results in Table 5, the use of the PhET media medium in learning states of matter and their changes showed a level of effectiveness in the very effective category according to Table 2, with a mean percentage of 84.01%. This effectiveness was reflected in understanding of the concept of states of matter and their changes (88.75%), improvement in learning outcomes (84.17%), correction of misconceptions (81.87%), and achievement of learning objectives (81.25%). These high scores indicate that the PhET media medium was able to help students visualize abstract science concepts through interactive simulations, so that students could explore and observe the relationship between concepts and phenomena more concretely. This finding is in line with Wieman et al. (2008), who explained that PhET simulations are designed to improve conceptual understanding through interaction and visualization of scientific phenomena. This result is also supported by Rutten et al. (2012), who showed that computer simulations can make a positive contribution to science learning, particularly in conceptual understanding. Critical reviews of science simulations also emphasize the importance of instructional design and supporting student reflection (Smetana & Bell, 2012).

Table 5. Summary of Questionnaire Results on Effectiveness and Practicality

No	Variable	Indicator	number of items	(%)
1	Effectiveness	Understanding of the concept of states of matter and their changes	4	88.75%
2		Achievement of learning objectives	3	81.25%
3		Improvement in learning outcomes	3	84.17%
4		Correction of misconceptions	2	81.87%
Mean				84.01%
5	Practicality	Ease of Use	5	80%
6		Learning Motivation	5	87%
7		Media Attractiveness	5	86.5%
8		Usefulness	5	80%
Mean				83.37%

The improvement in students' learning outcomes following the implementation of PhET media may be explained by the simulation's ability to make the microscopic nature of matter more accessible to learners. States of matter and changes of state involve particle-level processes that cannot be directly observed in everyday life. Through PhET simulations, students can visualize the arrangement, spacing, and movement of particles in solids, liquids, and gases. By manipulating the heating and cooling controls, students can also observe how changes in thermal energy are associated with changes in particle motion and the transition between states of matter. These visual representations help students connect macroscopic phenomena, such as melting, evaporation, and condensation, with their underlying microscopic explanations. Furthermore, the interactive features of the simulation allow students to explore different conditions and observe the resulting changes, potentially supporting active participation and conceptual understanding. This interpretation is consistent with Wieman et al. (2008), who discussed the potential of interactive PhET simulations to support science learning through visual representation and exploration. However, the extent to which these mechanisms contributed to learning in the present study should be interpreted in relation to the learning activities actually implemented. This interpretation is also consistent with research on students' conceptual pathways for the particulate nature of matter and the challenges of coordinating macroscopic and microscopic

representations (Johnstone, 1991; Talanquer, 2009; Adadan et al., 2010; Mayer, 2009).

The mean learning outcome score increased from 58.25 in the pretest to 83.75 in the posttest, while the proportion of students achieving learning mastery increased from 25% to 100%. Nevertheless, the reported mean N-Gain of 0.6008 (60.08%) remained within the moderate category. These findings are not contradictory because learning mastery and normalized gain represent different aspects of learning achievement. Learning mastery indicates whether students have reached a predetermined minimum achievement criterion, whereas N-Gain measures the proportion of the possible improvement achieved relative to the difference between the pretest score and the ideal maximum score. Consequently, all students may achieve the required mastery threshold even when the average normalized gain remains moderate. The moderate N-Gain suggests that, although substantial improvement occurred, the learning gains did not reach the threshold for the high category under the classification used in this study. This outcome may reflect differences in students' initial understanding, the difficulty of the assessed concepts, and the limited duration of the intervention. These factors, however, were not independently examined and should therefore be considered possible explanations rather than established causes.

The N-Gain findings are comparable to those reported by Siburian (2018), who investigated the use of the PhET mobile application for teaching states of matter to seventh-grade students and reported an N-Gain of 0.61 alongside very high student interest. The similarity between the normalized gains suggests a comparable pattern of moderate improvement in conceptual understanding across the two learning contexts. More recently, Fuentes et al. (2025) reported improved academic performance among Grade 7 students learning phases of matter through PhET interactive simulations, with their paired-samples t-test indicating a statistically significant pretest–posttest difference. Although these studies support the potential of PhET for learning about states of matter, differences in sample size, instructional implementation, assessment instruments, and analytical procedures limit direct comparisons of the magnitude of improvement. In addition, Banda and Nzabahimana (2021), in their review of 31 experimental and quasi-experimental studies, concluded that PhET simulations can support conceptual understanding and are particularly useful when integrated into active learning environments. Taken together, these findings suggest that the educational value of PhET lies not merely in presenting animated content but also in providing opportunities for learners to explore scientific representations and connect them with conceptual explanations.

The questionnaire findings provide a complementary perspective on students' experiences with PhET media. The perceived effectiveness score of 84.01% fell within the very high category, while the mean practicality score of 83.37% was classified as very practical according to the criteria used in this study. For practicality, learning motivation received the highest score (87%), followed by media attractiveness (86.5%). In contrast, ease of use and usefulness each received 80%, which falls within the practical category rather than the very practical category according to Table 2. This difference suggests that students responded particularly positively to the motivational and visual aspects of the simulations, while ease of use and perceived usefulness may represent areas for further improvement. For example, clearer instructions, structured worksheets, and teacher guidance may help students navigate the simulation and relate their observations more explicitly to learning objectives. Importantly, the questionnaire percentages describe students' perceptions of the medium, whereas N-Gain quantifies changes in their test performance. Therefore, the very positive questionnaire ratings do not necessarily imply that learning gains must fall within the high N-Gain category. The two sets of results measure complementary but distinct dimensions: students' perceptions of the learning medium and their demonstrated improvement in assessed learning outcomes. Accordingly, the questionnaire results support the conclusion that PhET was positively perceived in terms of effectiveness and practicality, while the N-Gain results indicate moderate improvement in learning outcomes.

Despite these encouraging findings, several limitations should be considered when interpreting the results. First, the study involved only 20 seventh-grade students from one school, which limits the generalizability of the findings to other student populations and educational settings. Second, the *One-Group Pretest-Posttest Design* did not include a control or comparison group (Shadish et al., 2002). Consequently, the observed improvement cannot be attributed exclusively to PhET media because other factors, such as regular classroom instruction, students' familiarity with the test content, repeated exposure to the same test items, and changes in students' understanding over time, may also have contributed to the difference between pretest and posttest scores. Third, the study was conducted over a limited period, and therefore the retention of students' conceptual understanding was not established. Future research should involve larger and more diverse samples, include comparison groups, and examine whether learning gains are maintained through delayed posttests. Further investigations could also explore how structured inquiry activities and teacher

guidance influence the relationship between students' engagement with PhET simulations and their conceptual understanding of states of matter and changes of state. Notwithstanding these limitations, the findings provide context-specific empirical evidence of improved learning outcomes and positive student perceptions following the use of PhET media at SMPN 2 Watubangga.

Conclusion

Based on the results of the study, the use of the PhET media medium in the topic of states of matter and their changes was shown to improve students' learning outcomes, as indicated by the increase in the mean score from 58.25 in the *pretest* to 83.75 in the *posttest*, the increase in learning mastery from 25% to 100%, and an N-Gain of 0.6008 (60.08%), which falls into the moderate category. These findings are reinforced by questionnaire results on the effectiveness and practicality of the medium, which show that the PhET media medium has an effectiveness level of 84.01% (very effective) and a practicality level of 83.37% (very practical). Thus, the PhET media medium is not only effective in helping students understand concepts, achieve learning objectives, and correct misconceptions, but also practical, engaging, and able to increase learning motivation through interactive exploration experiences. Overall, this study shows that the PhET media medium is a relevant alternative learning medium for supporting science learning, particularly on the topic of states of matter and their changes, especially when learning requires visualization and more concrete experimental experiences.

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Y.P. contributed to the conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft preparation, and project administration. S.M.A. contributed to data collection, investigation, validation, and data curation. S.S.A.B. contributed to validation, formal analysis, and writing—review and editing. A.E.S.N.A. contributed to investigation, visualization, and writing—review and editing. F.M. contributed to investigation, validation, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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