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Using PhET simulations to improve grade XII students' understanding of electrostatics during the COVID-19 pandemic at SMA Negeri 2 Donggo

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ABSTRACT

Electrostatics requires students to interpret processes that are difficult to observe directly, while limited laboratory equipment and pandemic-related disruption can restrict opportunities for investigation. This study examined changes in conceptual understanding, lesson implementation, and student responses following the use of PhET simulations at SMA Negeri 2 Donggo, Bima Regency, Indonesia. A single-group before-and-after classroom intervention involved 32 Grade XII science students during the first semester of the 2020/2021 academic year. Although described as experimental in the original manuscript, the reported design included neither random assignment nor a comparison group. Data were obtained through learning-process observations, worksheets, concept assessments, and student response forms. The mean concept score increased from 68.20 to 74.06, a gain of 5.86 score points. The number of students meeting the school's mastery criterion increased from 22 to 28, corresponding to 68.75% and 87.50%, or an increase of 18.75 percentage points. The minimum score increased from 41.18 to 55.00, while the maximum increased from 82.35 to 90.00. Lesson implementation received 38.5 of 44 possible points, an index of 87.50%. The response table reported 180 of 210 possible points, an index of 85.71%, but inconsistent respondent counts require verification. The findings indicate improved recorded achievement and favorable classroom responses following simulation-supported instruction. Because individual assessment data, instrument details, and a control condition were unavailable, the results support a classroom description rather than a causal estimate of PhET effectiveness.

Keywords: PhET Interactive Simulations; electrostatics; conceptual understanding; physics education; COVID-19 pandemic

INTRODUCTION

Electrostatics introduces students to electric charge, interactions between charges, electric fields, and electric potential. Understanding these ideas requires connecting observable phenomena with models of processes that cannot be seen directly. Research on difficulties with static electricity and a study of PhET-supported electrostatics instruction identify conceptual understanding as a continuing challenge in physics education (Doğru, 2021; Uwambajimana et al., 2023). Visual representations may help students examine these processes, but their instructional value depends on how they are used.

At SMA Negeri 2 Donggo in Bima Regency, the teacher reported limited equipment for demonstrating electrostatic phenomena, including a shortage of electroscopes. Instruction generally relied on textbooks, charts, diagrams of charge arrangements, and a limited range of

animations. Some students were described as inattentive or confused during teacher explanations. These observations motivated a classroom intervention using interactive simulation to provide an additional representation of electrostatic interactions.

The COVID-19 pandemic intensified the need for adaptable learning resources. Research on teachers' adaptation and readiness during school closures shows that continuity of instruction depends on competence, preparation, and the conditions of implementation (S. K. Howard et al., 2021; Kaden, 2020; König et al., 2020). A school-level review of emergency remote teaching also indicates substantial differences between settings (Al Mazrooei et al., 2022). These studies frame the intervention's pandemic context without implying that all participating students experienced the same form of remote instruction.

PhET Interactive Simulations, developed at the University of Colorado Boulder, provides research-based interactive resources for science and mathematics. The documented example in this study was Balloons and Static Electricity. The official project describes simulations as supporting inquiry and making otherwise invisible processes visible (PhET Interactive Simulations, n.d.). This study uses the official project name, rather than the inconsistent expansion of the acronym in the original manuscript. It does not attribute programming or animation development skills to students simply because they used a simulation.

A review of PhET studies provides evidence that simulations can support conceptual understanding within active learning environments (Banda & Nzabahimana, 2021). Meta-analyses and reviews of digital tools and virtual laboratories also provide a rationale for examining their use in science instruction (Hillmayr et al., 2020; Santos & Prudente, 2022). However, those findings cannot substitute for evidence from this classroom, and improvements observed after an intervention do not automatically establish that the simulation caused them.

The study therefore addresses three questions: how students' recorded electrostatics achievement changed after simulation-supported instruction; how observers evaluated lesson implementation; and how students responded to the use of the resource. Its contribution is a descriptive account of a Grade XII physics intervention under constrained classroom conditions, with attention to the distinction between achievement, implementation, and perceived interest.

LITERATURE REVIEW

Interactive simulation and conceptual understanding

Interactive simulations allow learners to change aspects of a represented situation and observe the consequences. In physics, this can create opportunities to connect diagrams, actions, and explanations. The PhET review by Banda and Nzabahimana and an electrostatics study in Rwanda provide directly relevant evidence about conceptual understanding (Banda & Nzabahimana, 2021; Uwambajimana et al., 2023). A separate study among Malawian physics students examines both motivation and achievement, illustrating that these outcomes require distinct measures (Banda & Nzabahimana, 2023).

Recent Indonesian research also considers PhET as a substitute for unavailable practical tools in teaching static electricity (Ismalia et al., 2022). Another Indonesian classroom study combines PhET with contextual teaching and learning in electromagnetic induction (Sukamto, 2022). Although the latter concerns a different topic, it provides a relevant example of integrating simulation with an instructional approach. Neither study establishes that all physics topics or all school settings respond in the same way.

Virtual laboratories and physical experiments offer partly different opportunities. A systematic review of combined real and virtual experiments and a second-order review focused on secondary STEM education indicate that integration and teacher support matter (Fadda et al., 2022; Wörner et al., 2022). Simulations may extend access to representations and repeatable exploration, while practical work can develop skills not necessarily captured by a concept test. The present study did not measure laboratory handling skills and therefore makes no claim that simulation replaced every function of a physical laboratory.

Evidence from a general university physics laboratory provides another example of virtual experiments, although its higher-education population limits direct transfer to Grade XII (Hamed & Aljanazrah, 2020). A meta-analysis of guided inquiry with virtual laboratories in Indonesian senior high schools is more closely aligned with the present educational level (Syahwin et al., 2022). Together, these studies support considering the instructional guidance surrounding simulation rather than treating the software as a self-sufficient intervention.

Guidance, representation, and cognitive demands

A simulation can display information without ensuring that students attend to the relevant relationship. Research on multimedia learning and cognitive load emphasizes the design of

explanations and the management of processing demands (Noetel et al., 2022; Sweller, 2020). Work on instructional video and distracting details provides additional guidance for selecting purposeful visual material (Mayer et al., 2020; Sundararajan & Adesope, 2020). These principles are relevant to introducing a simulation clearly and directing students toward the concept being investigated.

Emotional design research examines how features of multimedia material relate to learning, but visual appeal should be distinguished from conceptual understanding (Wong & Adesope, 2021). Generative learning research emphasizes students' construction of explanations, drawings, and other representations, with developmental differences affecting the demands of particular strategies (Brod, 2021; Fiorella, 2023). A review questioning whether digital learning should always be active further cautions against equating visible activity with successful learning (Skulmowski, 2024).

Accordingly, a useful simulation task should require students to predict or explain a relationship rather than merely manipulate controls. The original procedure involved identifying charge concepts, drawing interactions, selecting a representation, examining a simulation, and using it during learning. These stages offer opportunities for repeated attention to the same content. They do not, by themselves, establish improvement in higher-order thinking or scientific inquiry skills.

Feedback, practice, and discussion

Feedback may help students compare their explanations with the evidence presented by a simulation. Meta-analytic research on educational feedback shows why the nature of feedback matters, while classroom research on retrieval practice supports revisiting previously learned content (Agarwal et al., 2021; Wisniewski et al., 2020). In the present study, repeated concept examination is reported, but no separate retrieval-practice intervention or feedback scale was administered.

Peer assessment and writing-to-learn are additional instructional options supported by research (Double et al., 2020; Graham et al., 2020). Students could, for example, explain a charge interaction in writing or evaluate another student's explanation. These activities are recommendations for extending the approach, rather than procedures assumed to have occurred in this intervention. Evidence on active learning in undergraduate STEM also provides a broader

rationale for purposeful student involvement, with an explicit difference in educational level (Theobald et al., 2020).

Motivation and student responses

Students may find an interactive resource appealing without demonstrating durable conceptual learning. Self-determination theory distinguishes forms of motivation, and meta-analyses examine their relationships with learning outcomes and their antecedents (Bureau et al., 2022; J. L. Howard et al., 2021; Ryan & Deci, 2020). Research on autonomy-supportive teaching also identifies ways teachers can support participation (Reeve & Cheon, 2021). These sources suggest useful questions about student experience, but the study's response form does not establish a validated measure of intrinsic motivation.

For this reason, favorable responses, successful implementation, and achievement should be analyzed separately. A response index describes how a questionnaire was scored; it is not necessarily the proportion of students who endorsed an item. Similarly, an implementation score indicates how observers rated the lesson, rather than how many students understood electrostatics. Keeping these meanings separate is essential when interpreting the original result tables.

Teacher competence and implementation support

Teachers need to connect a simulation with content objectives, learner needs, and assessment. A digital competence framework and an umbrella review of teachers' roles in educational digitalization both support this broader conception of competence (Falloon, 2020; Wohlfart & Wagner, 2023). Research on teachers' perceptions of technology integration and lesson-planning expertise highlights the importance of pedagogical judgment alongside technical skills (Akram et al., 2022; Backfisch et al., 2020).

Models of technology integration can help teachers consider how instructional components fit together (Tondeur et al., 2021). Science teachers' accounts of interactive simulations provide directly relevant perspectives on practical classroom use (Ben Ouahi et al., 2022). Evidence on effective professional development and school leadership further suggests that implementation should be supported through purposeful learning opportunities and organizational conditions (Darling-Hammond et al., 2020; Leithwood et al., 2020; Sims & Fletcher-Wood, 2021). The involvement of the principal and school supervisor as observers in this study provides

implementation information, although their participation does not constitute an independent evaluation of causal effectiveness.

METHODS

Design, setting, and participants

The intervention involved one existing class of 32 Grade XII science students at SMA Negeri 2 Donggo, Bima Regency, Indonesia. The Indonesian methods identify the first semester of the 2020/2021 academic year; the original English abstract instead mentions the second semester. This revision follows the Indonesian methods description, with the semester to be checked against the teaching records.

The original manuscript describes the method as experimental. The procedures and results supplied, however, document a single-group before-and-after classroom intervention. No comparison group, random allocation, or counterfactual condition is reported. The study is therefore described according to the available design information. It is not recast as classroom action research because the supplied methods do not describe action-research cycles.

Materials and instructional procedure

The teacher used PhET as an additional resource for representing electrostatic phenomena. The reported access sequence was to visit the PhET website, select a physics simulation, and choose Balloons and Static Electricity. The precise software version, device allocation, and frequency of use were not supplied. The intervention's outcomes are consequently not attributed to a particular version, delivery platform, or pattern of individual access.

The broader teaching content included charge, electrical force, electric fields, potential, and parallel-plate capacitors. However, Balloons and Static Electricity is the only specific simulation identified in the source. The record does not show which resources, if any, supported the other topics. The study therefore does not claim that this one simulation taught the complete electrostatics unit.

The reported concept-learning sequence comprised selecting a theme related to charge; identifying concepts within that theme; drawing charge interactions; selecting an appropriate visual representation and examining simulation or animation; and using the simulation during learning. These stages were intended to encourage repeated examination of the content. The

available account does not provide the worksheets or sufficient detail to determine whether students created digital animations themselves.

Lesson implementation was organized into an introduction, core activities, and closure. The introduction included explaining objectives, orienting students, planning media use, and explaining operation. Core activities involved facilitating, observing, and evaluating the phases identified in the manuscript as define, design, develop, and revise. Closure included a summary and a final worksheet task. This terminology is retained as an account of the observed lesson; it is not treated as evidence of a separately validated instructional design model.

Instruments and data collection

Data sources were learning-process observation sheets, student worksheets, performance assessment, concept achievement tests, and student response forms. The school supervisor and principal served as the two lesson observers. Their observations concerned the introduction, core activities, and closure. Student responses concerned enjoyment, attractiveness, ease of understanding and use, conceptual clarity, learning support, and interest in using PhET for other physics topics.

The source does not provide the test items, item number, scoring scheme, reliability, questionnaire anchors, category boundaries, or evidence of instrument validation. It also does not state the numerical minimum mastery criterion used for the physics test. The reported numbers of students reaching mastery are retained, but no threshold of 75 or another score is assumed.

Descriptive analysis and checks on aggregation

Achievement was summarized by the reported mean, minimum, maximum, and number reaching the school's mastery criterion before and after the intervention. Score changes were calculated by subtraction and expressed in score points. Mastery percentages used the class size of 32. Changes between mastery percentages were expressed in percentage points, rather than being confused with relative percentage increases.

The implementation index was calculated as the reported obtained score divided by the maximum possible score, multiplied by 100. The response index used the same ratio for the scores in the response table. These indices do not represent percentages of students. Because the original response narrative refers to 30 students whereas the methods identify 32 participants, a response rate was not calculated.

Only descriptive comparisons were made. Individual paired records and variability measures were not supplied, so no paired significance test, standardized effect size, or normalized gain was calculated. The earlier introductory score of 48.83 was not treated as the pre-intervention mean because its assessment context was unspecified; the before-and-after table reports 68.20 as the initial mean.

RESULTS AND DISCUSSION

Recorded conceptual understanding

Table 1 presents the before-and-after achievement summaries. The mean increased from 68.20 to 74.06, a difference of 5.86 score points. The minimum increased by 13.82 points, from 41.18 to 55.00, and the maximum increased by 7.65 points, from 82.35 to 90.00. These changes describe score differences and should not be reported as percentage increases.

Table 1. Electrostatics achievement before and after the intervention (N = 32)

Indicator	Before	After	Change
Mean concept score	68.20	74.06	+5.86 score points
Students reaching mastery, n	22	28	+6 students
Students reaching mastery, %	68.75	87.50	+18.75 percentage points
Minimum score	41.18	55.00	+13.82 score points
Maximum score	82.35	90.00	+7.65 score points

Source: Original achievement table and results narrative. Mastery percentages were recalculated from 22/32 and 28/32, correcting the original 68.72% and 18.78-point difference. The numerical mastery threshold and individual paired scores were not supplied.

The number reaching mastery increased from 22 to 28 students. With 32 participants, the corresponding percentages are 68.75% and 87.50%, an increase of 18.75 percentage points. The original table gives 68.72% and a difference of 18.78; these values have been corrected using the supplied counts and denominator. The final 87.50% is the proportion reaching mastery, not the magnitude of improvement in the mean concept score.

The original table classifies the initial achievement as poor and the final achievement as good. The category boundaries were not supplied, so these labels are retained only as source descriptions and are not treated as independently verified standards. The higher final minimum and maximum do not establish that every individual student improved, because individual paired scores were unavailable.

Lesson implementation

Table 2 reports the overall implementation score and the stage-specific observation means. The obtained total was 38.5 of 44 possible points, producing an implementation index of 87.50%. The original manuscript described this as very practical. The observed stages received means of 4.00 for the introduction, 3.25 for core activities, and 3.50 for closure. These means indicate that the core activities received the lowest reported stage rating.

Table 2. Lesson implementation and reported observation scores

Indicator	Reported value
Obtained total score	38.5
Maximum possible total score	44
Implementation index: 38.5/44 × 100	87.50%
Source category	Very practical
Introduction: reported stage mean	4.00
Core activities: reported stage mean	3.25
Closure: reported stage mean	3.50

Source: Original implementation table and observation narrative. Two observers were the school supervisor and principal. Stage means and overall total are distinct summaries; the item-level rubric, weights, category boundaries, and agreement between observers were not reported.

The total of 38.5 should not be labeled an average stage score. Without the complete observation rubric, the numbers of items and weights for each stage cannot be reconstructed. The result supports describing the lesson as favorably rated by the two observers under the source rubric. It does not demonstrate instrument reliability, inter-rater agreement, implementation consistency across different teachers, or student mastery.

The lower core-activity rating suggests an area for continued classroom review. Future observation could identify whether students understood task directions, whether explanations accompanied simulation use, and whether the teacher checked misconceptions. Research on guidance in virtual laboratory instruction and teachers' views of interactive simulations provides a relevant context for these questions (Ben Ouahi et al., 2022; Syahwin et al., 2022). The present records do not identify which individual core activities were difficult.

Student responses

The response table gives an obtained score of 180 and a maximum score of 210. Their ratio is 85.71%, which the source describes as very interesting. This is an aggregate response index

rather than evidence that 85.71% of participants responded positively. Table 3 preserves the reported mean of 26.42, while making clear that its unit and aggregation rule were not explained.

Table 3. Student response scores and unresolved reporting details

Indicator	Reported value	Interpretation
Mean	26.42	Unit and aggregation rule not supplied.
Obtained total score	180	Retained from the source response table.
Maximum possible score	210	Retained; item and respondent structure unspecified.
Response index: 180/210 × 100	85.71%	Aggregate score ratio, not percentage of students.
Source category	Very interesting	Category boundaries not supplied.
Respondent count in narrative	30	Methods state 32 study participants; difference unexplained.
Positive-response narrative	26; 80.09%	26/30 = 86.67%; original percentage cannot be reconciled with these values.

Source: Original response table and narrative. The response table incorrectly labels its percentage as practicality; this revision labels it as a response index according to the section's stated purpose. Respondent count and item-level scoring require confirmation.

The response narrative indicates that students enjoyed learning with PhET, found it attractive and easy to use, believed it clarified concepts and supported learning, and expressed interest in using it for other physics topics. Item-specific counts were not supplied, so these statements remain reported impressions rather than quantified questionnaire results.

The narrative also refers to an average of 26 positive responses among 30 students and a percentage of 80.09%. These figures are inconsistent: 26 divided by 30 is 86.67%, and the methods give a class size of 32. The records do not establish whether two students did not answer the questionnaire or whether a different aggregation was used. The respondent count, the reported mean, and the item-level scores require verification before making a claim about the proportion of students expressing positive responses.

Interpreting the achievement pattern

The recorded improvement is consistent with a role for repeated examination and visual representation of charge interactions. Students were described as identifying concepts, drawing interactions, and revisiting them through simulation. Reviews of PhET learning and secondary digital tools provide a plausible instructional rationale for this sequence (Banda & Nzabahimana, 2021; Hillmayr et al., 2020). However, additional practice, teacher explanation, familiarity with

the test, or other classroom changes could also account for the observed before-and-after difference.

A conceptual explanation should go beyond saying that the simulation was attractive. Multimedia and generative learning research suggests that students benefit when visual information is connected to a focused explanatory task (Fiorella, 2023; Noetel et al., 2022). In this intervention, the reported sequence offered such opportunities, but the available achievement summaries do not show which concepts improved or whether misconceptions persisted. Qualitative analysis of students' drawings and explanations would help answer these questions.

Research on virtual laboratories supports examining teacher guidance and the relation between virtual and practical activities (Fadda et al., 2022; Wörner et al., 2022). For this school, simulation provided an additional instructional option where equipment was limited. That practical value does not establish equivalence with every kind of laboratory experience. Future use should distinguish conceptual representation from equipment handling and inquiry skills, using measures appropriate to each outcome.

The favorable implementation and response indices complement the achievement results, but they measure different aspects of the classroom experience. Motivation research provides reasons to take student interest seriously while assessing learning independently (J. L. Howard et al., 2021). A resource that students like may still require clearer prompts or additional explanation. Teachers should therefore review completed worksheets and concept responses alongside questionnaire impressions.

Limitations and implications

The study has a small, single-class scope, no control condition, and incomplete information about instruments and lesson duration. The before-and-after summaries cannot identify individual change, estimate statistical uncertainty, or establish a causal effect. The numerical mastery threshold is unspecified, and the response records contain contradictory denominators and percentages. The semester also differs between the original Indonesian methods and English abstract.

These limitations do not invalidate the recorded classroom experience, but they constrain its interpretation. The defensible conclusion is that achievement summaries improved after simulation-supported instruction and that observers and the response table reported favorable

evaluations. General claims that PhET significantly increased higher-order thinking, intrinsic motivation, or practical laboratory competence would require additional data.

For future implementation, teachers should preserve the assessment rubric, state the mastery threshold, record individual paired results, and specify the simulation and device arrangements used. Observation records should retain item-level ratings from each observer, while response forms should identify the number of respondents and the calculation of each aggregate. Teachers could also add written explanations and peer review as instructional extensions, supported by evidence on writing-to-learn and peer assessment (Double et al., 2020; Graham et al., 2020).

CONCLUSION AND RECOMMENDATIONS

Among 32 Grade XII science students at SMA Negeri 2 Donggo, the reported mean electrostatics score increased from 68.20 to 74.06 following PhET-supported instruction. The number reaching the school's mastery criterion increased from 22 to 28 students, equivalent to 68.75% and 87.50%. The implementation score was 38.5 of 44 possible points, while the student response table reported 180 of 210 possible points. These indices indicate favorable evaluations under the original scoring arrangements, subject to clarification of the questionnaire records.

The findings support using PhET as an additional instructional resource for visualizing and discussing electrostatic phenomena in this classroom. The available design does not establish that the simulation alone caused the improvement, and contradictory response figures require verification. The numerical mastery threshold and study semester should also be confirmed from the original teaching records.

Teachers should connect simulation use to explicit conceptual questions, provide clear operating instructions, and assess students' explanations independently of their interest in the resource. School leaders and supervisors can support implementation through access to suitable devices, focused observation, and teacher learning opportunities. Subsequent research should use complete paired data, transparent instruments, and a comparison condition when the purpose is to estimate effectiveness.

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