e-ISSN : 3090-5354
Vol. 2, No.1, April 2026

3D E-Worksheet on Global Warming: Its Impact on High School Students' Critical Thinking Skills

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DOI : https://doi.org/10.26740/jdpe.v2i1.50339

Sections Info

Article history:
Submitted: December 24, 2025
Final Revised: January 3, 2026
Accepted: January 4, 2026
Published: January 5, 2026

Keywords:
3D E-Worksheet; Guided Inquiry; Global Warming; Critical Thinking Skills; PhET Simulation.

ABSTRACT

Objective: *This study aims to describe the implementation of the guided inquiry learning model assisted by a 3D e-worksheet on global warming, analyze improvements in students' critical thinking skills after the learning, and determine students' responses to the learning.* ***Method:*** *The study used a pre-experimental design with a pre-test and post-test group without a control group. The subjects were grade X students of SMA Negeri 1 Kebomas in three classes (experimental class and two replica classes). The research instruments included observation sheets for learning implementation, critical thinking tests (pre-test and post-test) based on Ennis indicators, and student response questionnaires. Data were analyzed using normality and homogeneity tests, paired t-tests, N-Gain, ANOVA, Cohen's effect size, and descriptive analysis of responses.* ***Results:*** *Learning implementation was categorized as very good, with meeting percentages of 86.30%, 89.81%, and 90.74%. There was a significant difference between pre-test and post-test scores (Sig. 0.000). The average N-Gain values in the three classes were 0.443, 0.554, and 0.396 (moderate category), indicating increased critical thinking skills. ANOVA results showed Sig. 0.000, meaning improvement varied across classes. Student responses were good, with average percentages above 70%, reflecting interest and new experiences in technology-based physics learning.* ***Novelty:*** *The novelty lies in integrating 3D e-worksheet, supported by PhET simulations, into a guided inquiry framework on global warming to train students' critical thinking skills, with consistency tested across three classes.*

INTRODUCTION

Technological developments and the demands of the 21st century bring the hope that education can shape students who not only master scientific concepts but also possess higher-order thinking skills, particularly critical thinking, collaboration, creativity, and technological and information literacy. Physics learning, as part of the natural sciences (IPA), is ideally designed to hone critical thinking skills so that students can assess information scientifically and make evidence-based decisions (Wulandari et al., 2021; Redjeki et al., 2023). At the same time, the development of physics is closely linked to technological advancements, so physics learning should be relevant, contextual, and able to foster conceptual understanding through real-life experiences close to students' lives (Zakaria et al., 2019; Villayah & Suliyanah, 2025). Therefore, integrating technology into learning is not merely an option but a necessity to create a practical, interactive, and meaningful learning process in the digital age (Idhan et al., 2025; Punzalan & Punzalan, 2025).

In fact, daily human activities contribute to greenhouse gas emissions in the atmosphere and trigger global warming, making this a persistent environmental issue discussed in various countries, including Indonesia (Fajeri, 2018; Dianjaya & Epira, 2020;

Al Zahroh et al., 2024). Global warming is not merely a discourse but a phenomenon that impacts human survival and demands that society have an adequate understanding of climate change to prepare for it (Çolak et al., 2025). Education plays a crucial role in raising awareness of the dangers of global warming, enabling students to understand scientific concepts and fostering a commitment to minimizing environmental damage caused by human activities (Habibah et al., 2025). As the next generation, students are expected to develop ideas for reducing global warming through observation and the use of diverse learning resources, including the internet and digital media (Ariani et al., 2024). Thus, global warming material provides highly contextual and relevant content for developing critical thinking and scientific literacy in schools.

However, the reality of learning in schools demonstrates a gap between expectations and implementation. Based on interviews with physics teachers, students still lack the opportunity to understand concepts and relate them to various real-world situations deeply. Students also have not conducted many hands-on experiments through simple lab work on global warming, resulting in suboptimal levels of scientific inquiry and active student engagement. This situation tends to make learning monotonous, lacking variety and authentic learning experiences, potentially hindering the development of critical thinking skills (Sari et al., 2024; Remigio et al., 2025). However, critical thinking development can be strengthened through learning that provides space for investigation, observation, and a structured and efficient scientific process (Zhou et al., 2025). Furthermore, survey findings indicate that most students find physics difficult to understand because learning still focuses on textbooks or similar teaching materials. In contrast, students tend to prefer learning with a broader range of media (Fadillah et al., 2025). This situation underscores the need for innovative strategies and media to enable students to engage in more active, meaningful learning.

One relevant approach to addressing these issues is inquiry-based learning, particularly guided inquiry. The guided inquiry model positions students as active subjects, encouraging them to formulate problems, formulate hypotheses, collect data, test hypotheses, and conclude. This enables them to practice critical and analytical thinking in solving problems independently (Peeters et al., 2016; Fonseca et al., 2024). In science teaching, this model has been shown to facilitate students' exploration and discovery of needed information and positively impact their mental development and scientific attitudes (Hasmawati et al., 2023; Martins-Loução et al., 2020; Ocak et al., 2021). Furthermore, physics learning is inseparable from experimentation, as demonstrations can increase student engagement and enhance learning effectiveness (Hamed & Aljanazrah, 2020; Ocholla et al., 2025). Therefore, guided inquiry learning, which emphasizes investigation and experimentation, is a suitable approach to global warming, as it is conceptual and contextual and not dominated by formulaic calculations.

Previous research also reinforces the urgency of using digital teaching materials to support learning models that foster Encourage critical thinking. PBL-based e-worksheet supported by PhET simulations has been shown to potentially improve students' critical thinking skills, as evidenced by increases in pretest and posttest scores. However, the N-

Gain value is still relatively low (0.22) (Aditya & Viyanti, 2025). Another study found that developing a worksheet using a guided inquiry model produced a product suitable for practicums and honed the critical thinking skills of high school students (Suhirman & Prayogi, 2023). Furthermore, a physics e-worksheet with problem-based 3D Pageflip was rated very good by validators and suitable for use as a learning tool (Distrik et al., 2024), while an interactive e-worksheet based on Wizer.me was deemed practical and effective, with high responses from both teachers and students (Holiwarni et al., 2025). However, previous studies also have limitations, for example, some e-worksheets require ample storage space for installation on devices. At the same time, specific platforms, such as Wizer.me, have limited premium features that require payment. These limitations highlight the need for innovative digital learning media that are more engaging, flexible across devices, and that support inquiry-based learning without significant technical barriers (Juniantari et al., 2025; Nurhasanah et al., 2025).

Based on these gaps and a review of previous research, this study proposes a solution: implementing a guided inquiry learning model using a 3D e-worksheet on global warming. The 3D e-worksheet was developed to include concise material, simple lab procedures, visual simulations of the greenhouse effect, and questions aligned with Ennis' critical thinking indicators. This allows students to experience active, contextual learning that stimulates critical thinking skills (Haritani et al., 2021). The advantage of an e-worksheet is that it can be accessed on various devices (computers, laptops, and mobile phones). The 3D Pageflip Professional display enables the integration of text, images, animations, videos, audio, and interactive components, making learning more engaging and efficient (Adawiyah et al., 2022; Istichomah et al., 2022; Hamidah et al., 2023; Distrik et al., 2024). Thus, the purpose of this study is to describe the implementation of guided inquiry assisted by a 3D e-worksheet, describe the improvement in students' learning outcomes in the critical thinking domain after implementation, and describe students' responses to the learning. The novelty of the study lies in the integration of guided inquiry with a 3D e-worksheet on global warming, designed to facilitate investigation and visual simulation and to include questions based on Ennis's critical thinking indicators, because previous studies have not specifically examined the implementation of this combination in global warming material.

RESEARCH METHOD

Research Design

This study employed a quantitative, pre-experimental research design. The research design used was a repeated pretest–posttest group design without a control class. This design was chosen to describe the effects of the treatment and test the consistency of results across multiple classes receiving the same treatment. Each class was given a pretest (O1) before the treatment and a posttest (O2) after the treatment. Treatment (X) involved implementing a guided inquiry learning model, assisted by a 3D e-worksheet on global warming (Siregar et al., 2023; Fauzi & Habibah, 2025). The research scheme is shown as follows:

$O_1 – X – O_2$ (for the experimental and replication classes).

Research Setting and Participants

The research was conducted at SMA Negeri 1 Kebomas, Gresik Regency, in the even semester of the 2023/2024 academic year using the Independent Curriculum. The study population was all students from grades X-1 to X-10. The research sample was selected using a purposive sampling technique, based on the suitability of the research needs, namely grades X-6, X-7, and X-8. Grade X-7 served as the experimental class, while grades X-6 and X-8 served as replication classes to evaluate the consistency of the treatment results (Memon et al., 2024).

Variables

This study involved three types of variables. First, the independent variable was the implementation of a 3D e-worksheet using a guided inquiry learning model. Second, the dependent variables included: (1) learning implementation, (2) improvement in critical thinking skills, and (3) student responses. Third, the control variables held constant throughout the study were the school, the global warming material, the learning time allocation, the test instruments, and the teaching staff, to minimize the influence of external factors on the research results.

Learning Tools and Treatment

The treatment in this study is the implementation of guided inquiry learning using a digitally compiled 3D e-worksheet that includes initial phenomena, problem formulation, hypotheses, experimental steps, data analysis, conclusions, and the communication of results. The e-worksheet product includes a PhET Interactive Simulation (Greenhouse Effect) as a 3D visualization to help students conduct virtual experiments independently and connect concepts to the phenomenon of global warming (Wahdah et al., 2024). The learning stages follow the syntax of guided inquiry, namely problem orientation, problem formulation, hypothesis formulation, data collection through experiments/simulations, hypothesis testing, and conclusion drawing (Sokołowska, 2018; Carbogim et al., 2019).

Instruments and Data Collection

1. Research data was collected using three methods: observation, testing, and questionnaires.
2. Observation sheets were used to assess learning effectiveness by measuring the alignment of teacher activities with the guided inquiry syntax. Observations were conducted by two observers using a 1–4 rating scale.
3. The Critical Thinking Test, a multiple-choice test, was administered at the pretest and posttest stages (using the same questions). The critical thinking indicators, according to Ennis, include: providing simple explanations, building basic skills, concluding,

providing further explanations, and organizing strategies and tactics (Riezandi & Nurita, 2022).

Validity of Instruments

Two expert validators validated the research instruments and learning tools. The validated tools included teaching modules, 3D e-worksheet, handouts, pretest-posttest questions, response questionnaires, and learning implementation observation sheets. The validity level refers to the criteria of the 1–4 score interval, where a score of 3.6–4.0 is categorized as very valid and can be used without revision (Adams & Wieman, 2011). The validation results showed that all tools and instruments were highly valid and suitable for use.

Data Analysis

Data analysis was conducted quantitatively using SPSS 25.0 and descriptive analysis.

1. Learning implementation was analyzed using the implementation percentage, using the formula:

   Percentage = (score obtained / ideal maximum score) × 100%.

   The percentage results were categorized into a rating scale: 81–100% (perfect), 61–80% (good), and so on (Habibullah et al., 2022).
1. Critical thinking skills were analyzed using prerequisite tests, namely the Shapiro–Wilk normality test and the Levene homogeneity test ($\alpha = 0.05$). If the data were normally distributed, a paired-samples t-test was conducted to determine whether the pretest and posttest scores differed significantly. If the data were not normally distributed, the Wilcoxon Signed Rank Test was used as a nonparametric test (Sulistyanto et al., 2022; Fiandini et al., 2023; Romadhon et al., 2024).
2. The level of improvement was calculated using normalized gain (N-gain) with the formula:

   $$N(g) = (S_{posttest} - S_{pretest}) / (S_{max} - S_{pretest}).$$

   The interpretation of N-gain follows Hake's (1999) categories: high (≥ 0.7), moderate (0.3–<0.7), and low (<0.3).
3. The consistency of improvement between classes was analyzed using one-way ANOVA if the N-gain data were normally distributed and homogeneous.
4. The magnitude of the treatment effect was analyzed using Cohen's effect size, with categories of very low (0.00–0.20), low (0.21–0.50), moderate (0.51–1.00), and strong (>1.00) (Prahani et al., 2021; Mas'udi & Maryani, 2024).
5. Student responses were analyzed descriptively by calculating the percentage of the total score relative to the ideal score, then interpreted using rating-scale criteria (Changiz et al., 2013; WU et al., 2024).

RESULTS AND DISCUSSION

Results

Implementation of Guided Inquiry Learning Assisted by 3D e-worksheet

Observations showed that all stages of the guided inquiry learning process were implemented very well. The percentage of learning implementation increased from the first to the third meeting, reaching 86.30%, 89.81%, and 90.74%, respectively, which is

considered very good. These findings indicate that the learning process followed the guided inquiry syntax and that the use of a 3D e-worksheet supported effective learning.

Table 1. Implementation level of guided inquiry learning assisted by 3D e-worksheet

Meeting	Implementation Percentage (%)	Category
1	86.30	Very Good
2	89.81	Very Good
3	90.74	Very Good

Data Prerequisite Testing (Normality and Homogeneity)

Prior to the effectiveness test, the pretest and posttest data were prerequisite tested. The Shapiro–Wilk normality test results showed that the pretest and posttest significance values for classes X-6, X-7, and X-8 were all greater than 0.05, indicating a normal distribution of the data. The Levene's homogeneity test also showed a significance value of 0.938 for the pretest (>0.05), indicating that the data had homogeneous variance.

Table 2. Prerequisite test results (normality and homogeneity) of pre-test and post-test data

Prerequisite Test	Class/Test	Statistict Test	Sig.	Decision
Normality (Shapiro–Wilk)	X-6 Pre-test	Shapiro–Wilk	0.088	Normal
	X-6 Post-test	Shapiro–Wilk	0.253	Normal
	X-7 Pre-test	Shapiro–Wilk	0.294	Normal
	X-7 Post-test	Shapiro–Wilk	0.077	Normal
	X-8 Pre-test	Shapiro–Wilk	0.082	Normal
	X-8 Post-test	Shapiro–Wilk	0.540	Normal
Homogenity (Levene – based on Mean)	Pre-test	Levene Statistic = 0.064	0.938	Homogen
	Post-test	Levene Statistic = 0.078	0.925	Homogen

Improved Critical Thinking Skills

Improved critical thinking skills were analyzed by comparing pretest and posttest scores. The test results showed an increase in scores after the treatment, indicated by a significance value of 0.000 (sig. < 0.05), indicating a significant difference between the pretest and posttest scores. Furthermore, a negative t-value indicates that the posttest scores were higher than the pretest.

Table 3. Paired Samples t-test results (pretest vs posttest)

Class	Test Pair	Sig. (2-tailed)	Decision	Interpretation
X-7	Pretest–Posttest	0.000	H_0 rejected	Significant difference
X-6	Pretest–Posttest	0.000	H_0 rejected	Significant difference
X-8	Pretest–Posttest	0.000	H_0 rejected	Significant difference

Furthermore, the n-gain calculation shows an increase in critical thinking skills in the three sample classes with a moderate category, namely the experimental class 0.443, replication 1 0.554, and replication 2 0.396.

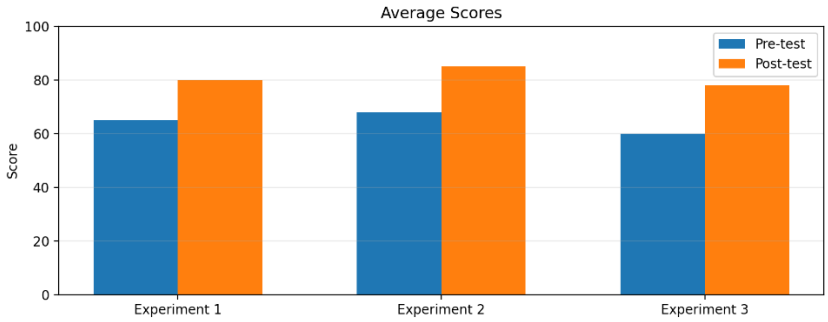

Figure 1. Comparison chart of average pretest scores

In detail, the highest critical thinking indicators were in the ability to conclude (85.2%) and provide further explanations (80.32%), which shows that inquiry learning assisted by e-worksheet 3D is effective in stimulating high-level thinking processes.

Table 4. Normalized gain (n-gain) of students' critical thinking skills

Class	Role in Study	n-Gain (Mean)	Interpretation
X-7	Experiment	0.554	Moderate
X-6	Replication I	0.443	Moderate
X-8	Replication II	0.396	Moderate

Consistency of improvement between classes (ANOVA)

To test the consistency of improvement in critical thinking skills between classes, an ANOVA test was conducted. The ANOVA results showed a significance value of 0.000, indicating a significant difference between groups. This finding indicates that improvement in critical thinking skills was not entirely uniform across the three sample classes.

Table 5. ANOVA test results (n-gain critical thinking ability)

Sumber Variasi	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.164	2	0.082	20.655	0.000
Within Groups	0.355	89	0.004		
Total	0.519	91			

Strength of Effect (Cohen's Effect Size)

In addition to score improvement, this study also calculated the effect size of the treatment using Cohen's d. The calculation results showed a d value of 1.56, which is considered strong, indicating that the implementation of the 3D e-worksheet with a guided inquiry model had a significant impact on improving students' critical thinking skills.

Student Responses to Learning

The results of the questionnaire showed that students gave a positive assessment of the guided inquiry learning process using the 3D e-worksheet. Overall, the average response rate was above 70%, categorized as good. In terms of interest, students found the 3D e-worksheet interesting and made learning more meaningful (85.20%), and provided new experiences related to science and technology (84.77%).

Table 6. Result of student responses to learning

No	Statement	Exp 1 (X-6)	Exp 2 (X-7)	Exp 3 (X-8)	Average
Inquiry learning model					
1	The application of the guided inquiry learning model was boring.	77.08	80.00	75.00	77.36 (B)
2	The application of the guided inquiry learning model made it easier for me to understand the material.	81.94	87.86	80.40	83.40 (SB)
3	The application of the guided inquiry learning model made it difficult for me to understand the concept of global warming in everyday life.	78.47	79.28	76.35	78.03 (B)
4	The application of the guided inquiry learning model improved my level of scientific inquiry.	77.78	78.57	78.38	78.24 (B)
3D e-worksheet learning media					
5	With the 3D e-worksheet, I'm not interested in this learning.	81.25	87.14	81.76	83.33 (SB)
6	With the 3D e-worksheet, I learned about the greenhouse effect in three dimensions.	88.89	84.28	82.43	85.20 (SB)
7	With the 3D e-worksheet, I gained new experiences about science and technology in education.	86.11	86.43	81.76	84.77 (SB)
8	With the 3D e-worksheet, I wasn't actively involved in experimenting.	75.69	85.71	76.35	79.25 (B)
Critical thinking skills					
9	The implementation of the guided inquiry learning model did not increase active learning.	81.25	82.86	79.73	81.28 (SB)
10	I can state the results of a research study.	81.94	79.28	79.73	80.32 (SB)
11	My thinking skills improved after learning about global warming.	84.72	82.86	79.05	82.21 (SB)
12	I cannot conclude a problem and determine the next course of action.	77.78	77.14	77.70	77.54 (B)

In addition, the questionnaire results showed that students felt that their critical thinking skills had increased after learning with percentages of 84.72%, 82.86%, and 79.05% respectively in the three classes.

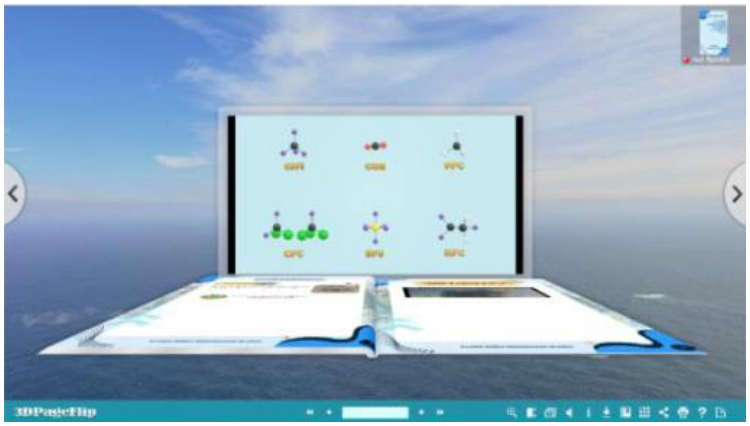

Figure 2. 3D e-worksheet display (optional) as visual media evidence

Overall, these findings confirm that 3D e-worksheet-based learning not only improves cognitive achievement, but is also well received by students.

Discussion

Implementation of the Guided Inquiry Learning Model Assisted by e-worksheet 3D

The implementation results showed that the guided inquiry learning model, supported by the 3D e-worksheet, performed very well, with percentages increasing at each meeting (86.30%; 89.81%; 90.74%). This finding indicates that the guided inquiry syntax can be implemented consistently and in a structured manner in physics learning on global warming. Exemplary implementation not only demonstrates teachers' readiness to manage the classroom but also indicates that the 3D e-worksheet digital tool can effectively support the learning process, including time management and classroom atmosphere.

This successful implementation also aligns with the principle of student-centered learning. During the lesson, the teacher acts as a facilitator. At the same time, students actively construct understanding through a series of problem-oriented activities, including formulating problems, developing hypotheses, conducting experiments, and drawing conclusions. This pattern aligns with Bruner's learning theory, which emphasizes the importance of direct student involvement in discovering knowledge through discovery-based learning (Chand, 2023). Thus, the guided inquiry model, supported by the 3D e-worksheet, is not only implemented according to syntax but also aligns with the primary objectives of 21st-century learning, which emphasize active engagement and the creation of meaningful learning experiences.

In the problem orientation and problem formulation stages, students are trained to observe phenomena through images and videos, then transform the information into problem formulations and hypotheses. This activity directly relates to the critical thinking indicators "providing simple explanations" and "focusing questions" (Zahara et al., 2024). The stages of group discussion, question-and-answer sessions, and teacher clarification also reinforce Vygotsky's view that social interaction with peers and teachers can foster higher cognitive development (Adams & Oliver, 2019). Therefore, high implementation of learning can be a strong indicator that the 3D e-worksheet can facilitate guided inquiry activities in accordance with the learning design.

Improving Critical Thinking Skills after Implementing the Guided Inquiry Learning Model Assisted by e-worksheet 3D

Statistical test results showed a significant difference between pretest and posttest scores (Sig. = 0.000 < 0.05), indicating that the guided inquiry model, supported by the 3D e-worksheet, significantly improved students' critical thinking skills. Furthermore, the increase based on the N-gain calculation fell within the moderate range (0.396–0.554), indicating that this learning strategy significantly improved critical thinking skills. However, the increase did not reach the high end of the range (Palloan et al., 2021). This finding supports previous studies that have shown that guided inquiry learning effectively improves critical thinking because students are involved in the processes of formulating problems, generating hypotheses, conducting investigations, and drawing conclusions (Septia & Edriati, 2019; Sutrisno et al., 2020; X. Zhao & Sun, 2022).

This improvement in critical thinking skills can be explained through the syntax of the guided inquiry model, which aligns with Ennis's (2011) critical thinking indicators. During the orientation, problem formulation, and hypothesis formulation stages, students develop the ability to provide simple explanations and ask scientific questions. The data collection phase through PhET experiments fosters fundamental skills, particularly in determining variables, conducting observations, and systematically recording data. Furthermore, hypothesis testing and the formulation of conclusions require students to provide further explanations, draw inferences from the data, and devise strategies to develop solutions related to global warming. Thus, all learning stages serve as a structured "practice space" for scientific thinking, comprehensively strengthening students' critical thinking skills.

Furthermore, the use of 3D e-worksheet contributes to improved learning outcomes. This medium offers animated videos and 3D simulations that visualize the greenhouse effect, helping students understand abstract concepts more concretely. This aligns with the notion that interactive media-assisted learning can enrich conceptual representation and enhance understanding, particularly in conceptual material (Zhao et al., 2022). However, variations in n-gain scores across classes indicate that improvements in critical thinking are not uniform. This variation is likely influenced by differences in class characteristics, student concentration during group discussions, and students' level of adaptation to digital-based guided inquiry learning strategies.

This finding is further strengthened by Cohen's effect size of 1.56, which is considered strong, indicating that this learning approach significantly improves students' critical thinking. This means that, even though the n-gain increase is moderate, the treatment's effectiveness can still be categorized as strong, given the significant and consistent changes in pretest-posttest scores across all three classes.

Student Responses to the Implementation of the Guided Inquiry Learning Model Assisted by e-worksheet 3D

The questionnaire results showed that student responses ranged from good to excellent, with an average percentage of each item above 70%. This indicates that the learning process was not only cognitively effective but also positively received by students. Positive responses were evident in statements stating that the guided inquiry model facilitated understanding of the material, and that the 3D e-worksheet provided a new experience of science and technology in education. Interestingly, the highest score was for the item stating that the 3D e-worksheet helped students understand the greenhouse

effect in three dimensions (85.20%). This indicates that the main strength of the 3D e-worksheet lies in its visualization, which transforms previously abstract concepts into easier-to-understand ones.

This finding aligns with Juliastari et al., (2022), who found that e-worksheets were perceived as more engaging and practical than printed worksheets. In this study, the 3D e-worksheet, based on 3D Pageflip and PhET simulations, enabled students to explore concepts independently, manipulate variables, and observe in real time the impact of changes in greenhouse gas concentrations on global temperature. These advantages make the learning experience more interactive and foster motivation. Furthermore, items related to improving critical thinking skills also received high responses (an average of 82.21% for the item on improving critical thinking skills after the global warming topic), thus confirming the statistical test results that learning does indeed impact critical thinking skills.

However, the lowest average was found for the item stating that guided inquiry learning was boring (77.36%). While still considered good, this can be explained by the fact that this was the first time students experienced guided inquiry learning with digital media, which required time to adapt. Furthermore, the relatively long inquiry stages can lead to boredom if the learning pace is not varied. Therefore, future implementations can consider strategies for varying activities and more flexible time management, for example, by more clearly dividing group assignments and using short icebreakers to maintain a conducive learning atmosphere.

Implications, Limitations, and Directions for Further Research

In general, the research results indicate that integrating guided inquiry, a 3D e-worksheet, and a PhET simulation is relevant to 21st-century physics learning because it can develop critical thinking and increase student engagement with contextual environmental issues. However, this study has limitations, namely the relatively short implementation period (three meetings), which limits the depth to which the long-term impact on critical thinking stability can be evaluated. Furthermore, the 3D e-worksheet requires adequate devices and an internet connection, which could pose accessibility challenges in schools with limited ICT facilities.

Therefore, further research can focus on long-term implementation to examine retention of critical thinking skills, as well as on developing a 3D e-worksheet with a smaller file size or offline features for broader implementation. By strengthening the aspects of access and implementation duration, this learning model has the potential to become a sustainable innovation in physics learning, particularly for conceptual topics such as global warming and the greenhouse effect.

CONCLUSION

Fundamental Finding: This study shows that the implementation of the guided inquiry learning model, assisted by a 3D e-worksheet, was very effective (86.30%–90.74%). This learning provided a significant increase in students' critical thinking skills (Sig. = 0.000), with a moderate n-gain (0.396–0.554) and a strong effect size (Cohen's d = 1.56). Students' responses were also positive, in the good-to-outstanding category. **Implication:** This finding confirms that integrating guided inquiry and a 3D e-worksheet assisted by a PhET simulation is effective for global warming material, increasing students' learning engagement and critical thinking skills, and is relevant to the demands of 21st-century learning. **Limitation:** This study has limitations in its short implementation period and

reliance on devices and internet connections, so that implementation in schools with limited ICT facilities may encounter obstacles. **Future Research:** Further research is recommended over a more extended period, with a larger sample size, and the development of a lighter 3D e-worksheet that can be accessed offline. Furthermore, application to other physics materials can be conducted to strengthen the generalizability of the results.

AUTHOR CONTRIBUTIONS

Salsabila Carissma Putri: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. **Eko Hariyono**: Supervision, Validation, Writing – review & editing.

CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no conflicts of interest, either financial or personal, that may have influenced the content or outcome of this study.

ETHICAL COMPLIANCE STATEMENT

This manuscript complies with research and publication ethics. The authors affirm that the work is original, conducted with academic integrity, and free from any unethical practices, including plagiarism.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING

The authors acknowledge the use of digital tools, including AI-based technologies, to support the research and writing processes of this article. Specifically, Mendeley was utilized for reference management and citation formatting, SPSS was used to conduct statistical analysis of the research data, and ChatGPT (OpenAI) was employed as a writing assistant to help refine language and organize the structure of the manuscript. All content generated with digital assistance was critically reviewed, validated, and revised by the authors to ensure academic integrity and ethical standards were maintained. The final responsibility for the content of this manuscript rests entirely with the authors.

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