Implementation of Air Expansion Simulation (AES) in physics education to increase student interest in environmental issues

Febiana Dinda Puspita[1], Afif Jauhari[1], Iqbal Ainur Rizki[2], Sujito[3], Nurita Apridiana Lestari[1]*

[1]Physics Education Department, Universitas Negeri Surabaya, Ketintang Street, Surabaya, 60231, Indonesia

[2]School of Education, Victoria University of Wellington, Kelburn Parade, Wellington, 6012, New Zealand

[3]Physics Education Department, Universitas Negeri Malang, Semarang Street No.5, Malang, 65145, Indonesia

*Corresponding author, email: nuritalestari@unesa.ac.id

Article History
Received: 15 November 2025
Revised: 3 January 2026
Accepted: 13 February 2026
Published: 25 March 2026

Keywords
Environmental awareness
Physics learning
Sustainable

Abstract
Increased pollution on Earth will cause environmental imbalance, which in turn will cause environmental damage. In addition, sustainable education is implemented to help address the problem by teaching students through direct experience. Therefore, a simple air expansion simulation is applied in sustainable physics learning as a simple demonstration of air velocity. With the implementation of sustainable physics education, it is hoped that students can understand air pressure and apply it in the environment to increase their interest in learning physics through environmental issues. Simple simulations are used to increase students' interest in learning physics. Based on the results obtained, the application of air expansion simulation (AES) as physics education increases students' interest and understanding, as shown by the results of responses that indicate strong agreement. Students can easily understand the material through simple air expansion simulations because during the learning process, students feel more interested. Students find it easier to understand because learning is done contextually, but learning is also done by involving students directly. Therefore, students find it easier to understand and master the material based on direct experience.

How to cite: Puspita, F. D., Jauhari, A., Rizki, I. A., Sujito, S., & Lestari, N. A. (2026). Implementation of Air Expansion Simulation (AES) in physics education to increase student interest in environmental issues. *Journal of Environment and Sustainability Education, 4*(1). 205–212. doi: 10.62672/joease.v4i1.158

1. Introduction

There has been an increase in pollution in Indonesia. One type of pollution is air pollution. In Indonesia, air pollution has increased in several regions. According to the BMKG, one region in Indonesia, Medan, has been recorded as unhealthy. The unhealthy category ranges from 55.5µg/m3 to 150.4µg/m3. In addition, there are 12 regions that have been recorded as moderate, with particulate concentrations ranging from 15.5µg/m3 to 55.4µg/m3 (BMKG, 2024). Particulate Concentration Chart (PM2.5) can be seen in Figure 1.

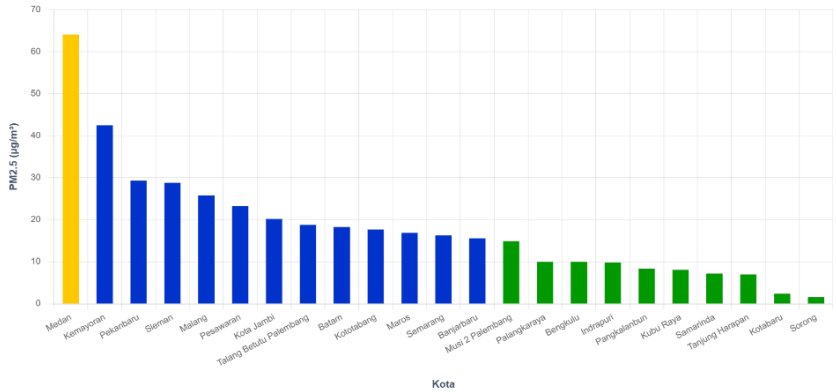


Figure 1. Particulate Concentration Chart (PM2.5)

doi: 10.62672/joease.v4i1.158
© 2026 The Authors
This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License
ISSN: 3025-0714

High levels of air pollution can be caused by several factors, such as vehicle exhaust, factory smoke, deforestation, and so on. Air pollution is an environmental problem that has a significant impact on urban areas and their surroundings (Indraj & Warpa, 2024; Maries et al., 2025). Based on BMKG data, CO2 concentrations in the October 2024 update reached more than 420 ppm.

Low interest in learning physics. Based on the results of the OECD PISA test, the results for physics were low. 31% of students achieved Level 3 basic critical thinking skills, which is much lower than the OECD average of 78%. This shows that students are capable of generating simple to moderate problem-solving ideas. Indonesia is also included in the high performance category in creative thinking at level 5 or above at 5%, but the OECD average is 27%, so the results achieved are far from the OECD average (PISA, 2023).

In scientific problem solving, Indonesia is far below the OECD average of -6%. Performance in mathematics, reading, and science is a strong predictor of creative thinking across all countries (Zapp, 2021). The need to implement education for sustainable development in science learning, especially physics learning, which encourages students to care more about the environment and instills a sustainable attitude (Stouthart et al., 2025; Prahani et al., 2025). The implementation of Education for Sustainable Development is used to improve students' problem-solving skills (Embacher, 2025; Qiroah & Lestari, 2024; Richter & Kickmeier-Rust, 2025).

In science education, socio-scientific issues can help students contribute to decision-making, understand the nature of science, gain experience in discussing controversial issues, and increase environmental awareness (Al-Kamzari & Alias, 2025; Lee et al., 2013). The education for sustainable development program can be developed by incorporating key sustainable development issues into teaching and learning, such as climate change, disaster risk reduction, and biodiversity issues, which are included in Socio-Scientific Issues(Moraes & Vianna, 2024;Wibowo et al., 2025). However, in reality, physics education in schools is often still abstract and focused on theoretical explanations, making it difficult for students to understand the concepts in depth. There is a need for learning innovations that can help students understand physics concepts in a more concrete and contextual manner (Fajar et al., 2022). One alternative that can be used is the use of simple simulation media designed based on phenomena that exist in the surrounding environment. Simple simulation media allow students to observe, manipulate, and understand physics concepts through visual representations and simple experiments that describe scientific processes in a more realistic manner.

In addition to helping simplify the understanding of concepts, the use of environment-based learning media can also increase students' awareness of environmental issues. Learning that links scientific concepts to real environmental conditions can encourage students to understand the relationship between science, human activities, and environmental sustainability (Herlanti et al., 2025; Tadena & Salic-Hairulla, 2021). This approach is in line with the concept of Education for Sustainable Development, which emphasises the importance of integrating environmental aspects into the educational process. Simple environment-based simulation media also provide opportunities for students to actively engage in the learning process through observation, exploration, and discussion activities. These activities can increase students' interest in learning, curiosity, and critical thinking skills in understanding the physical phenomena that occur around them (Nelson, 2010).

Participating in reflective discussions encourages participants to critically analyse the activities they have just completed, improving their understanding and consolidating their knowledge (Musengimana et al., 2025; Shulla et al., 2020). Therefore, A study entitled ‘Implementation of Air Expansion Simulation (AES) in Physics Education to Increase Student Interest in Environmental Issues’ needs to be conducted. This study is expected to provide an overview of how students respond to the application of simple environment-based simulation media in the physics learning process.

2. Method

This study used a quantitative descriptive method. It began with problem identification, followed by the design of an air expansion simulation (AES). After the first trial, it was implemented with students, and at the end of the implementation, a response questionnaire was given to the students to fill out. The results of the response questionnaire were analyzed and interpreted to arrive at a conclusion (Siedlecki, 2020). An overview of the flowchart of the quantitative descriptive research method used, as shown in Figure 2.

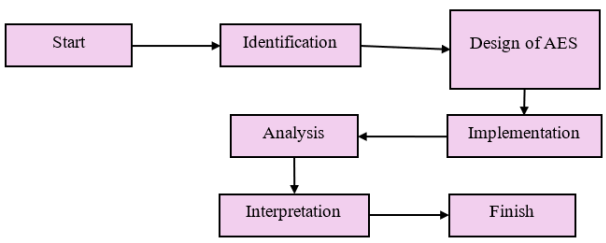


Figure 2. Flowchart Research Methode

Data collection in this study was conducted using a student response questionnaire. The questionnaire was given to students after the learning process was completed to find out their responses to the learning that had been carried out. The questionnaire instrument was compiled using a Likert scale with several answer choices that reflected the respondents' level of agreement with each statement. Data Analysis was tested for validity and reliability. Reliability was tested using Cronbach's Alpha coefficient with the help of IBM SPSS Statistics to determine the level of consistency of the instrument. The instrument was declared reliable if the Cronbach's Alpha value was greater than 0.70. After the instrument was declared valid and reliable, the questionnaire data were analysed descriptively to determine the percentage of student responses to the learning that had been implemented.

3. Results and Discussion

In this study, a questionnaire comprising 10 questions was distributed to gather the students' responses. **Figure** 3 presents the average results of students' responses to ten statements aimed at measuring their perceptions of the difficulty of Thermodynamics material and their preferences for more contextual, active, and issue-based learning methods. A 5-point Likert scale was used in this questionnaire, where an average value of 1 indicates the lowest level of agreement and a value of 5 indicates the highest level of agreement. Visual analysis of this diagram will help identify the main trends among students, particularly the extent to which recognize the difficulty of the material and the strength of their support for learning presented through case studies, current issues, and hands-on practice.

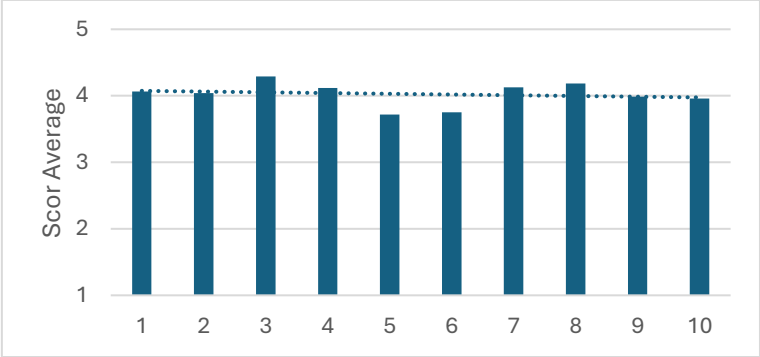


Figure 3. Average Questionnaire Score Results.

Based on the average results for each question, students agreed. These statements can be seen in Table 1. The questionnaire consists of 10 statements. In the first statement, "*Thermodynamics is a difficult subject,"* the average student agreed with the statement. In the second statement, "*Absorption of material is easier if taught contextually,"* the average student agreed with the statement. In the third statement, "*Material absorption is easier if taught with case studies of current issues*," the average student agreed with the statement. In the fourth statement, "*The teaching material encourages students to understand the relationship between environmental, social, and economic aspects*," the average student agreed with the statement. In the fifth statement, "*I feel that learning will be more interesting if it is presented in the form of case studies or projects*," the average student agreed with the statement. In the sixth statement, "*I am interested if the lesson raises issues*," the average student agreed with the statement. For the seventh statement, "*I am interested in learning if the teacher uses teaching aids or conducts demonstrations in front of the class*," the average student agreed with the statement. For the eighth statement, "*I am happy if I am given the opportunity to conduct experiments or hands-on practice in class*," the average student agreed with the statement. For the ninth statement, "*I feel more challenged and active when using teaching aids or technology in learning*," the average student agreed with the statement. For the tenth statement, "*I am used to doing experiments or practical work in groups*," the average student agreed with the statement.

Based on the results of the student response questionnaire analysis, it was found that, in general, students agreed with all of the statements presented. These results indicate that students have certain perceptions of thermodynamics learning and a preference for a more contextual, interactive, and experience-based learning approach (Saputri et al., 2025; Winarto et al., 2025). The first statement shows that students tend to consider thermodynamics material quite difficult to understand. This is a common finding in physics education because the concepts in thermodynamics are abstract, involving relationships between energy, temperature, and systems, thus requiring a learning approach that can help students build a deeper conceptual understanding. Students stated that the material would be easier to understand if it were taught contextually and using case studies of current issues. This finding shows that students find it easier to understand concepts when learning is linked to real phenomena that they encounter in their daily lives (Hariyono et al., 2024). The contextual approach enables students to connect scientific concepts with real-life situations, making the learning process more meaningful (Herlanti et al., 2025; Lee et al., 2013).

In addition, students also agreed with the statement that the teaching materials used could promote understanding of the relationship between environmental, social and economic aspects. This indicates that learning that integrates a sustainability perspective or Education for Sustainable Development can increase students' awareness of the interrelationship between scientific concepts and global issues (Lestari et al., 2024). Other findings indicate that students are more interested in learning that uses case studies and raises current issues. This is in line with a learning approach that emphasises active student involvement, encouraging students to explore real-world problems, work together in groups, and produce solutions or learning products (Hidaayatullaah et al., 2024). In addition, students also showed positive responses to the use of teaching aids, demonstrations, learning technologies, and experimental or hands-on activities. These responses indicate that learning methods involving direct experience can increase students' interest in learning and their active participation. Experimental activities and group work also provide opportunities for students to develop critical thinking, collaboration, and problem-solving skills (Solihah et al., 2024). Overall, these findings indicate that students tend to be more interested in contextual, issue-based learning that uses learning media and involves practical activities and group work. Therefore, teachers need to design more innovative, student-centred learning so that abstract physics concepts, particularly in thermodynamics, can be understood more effectively. Questionnaire can be seen in Table 1.

Table 1. Questionnaire

No	Statement
1	Thermodynamics is a difficult subject.
2	The material is easier to absorb if it is taught in a contextual manner.
3	The material is easier to absorb if it is taught using case studies of current issues.
4	The teaching material encourages students to understand the relationship between environmental, social, and economic aspects.
5	I feel that learning would be more interesting if it were presented in the form of case studies or projects.
6	I am interested if the lesson raises issues.
7	I am interested in learning if the teacher uses teaching aids or conducts demonstrations in front of the class.
8	I am happy if I am given the opportunity to conduct experiments or hands-on practice in class.
9	I feel more challenged and active when using teaching aids or technology in learning.
10	I am used to conducting experiments or practice in groups.

The average results of the questionnaire, which showed high student agreement with all ten statements collectively, concluded that there was a strong and clear preference among students for relevant and active learning methods. Although students acknowledged that thermodynamics material was somewhat difficult, firmly believed that the material would be easier to absorb if it was presented in a contextual manner and through case studies of current issues. This preference is reinforced by the desire for teaching materials to connect environmental, social, and economic aspects, which makes learning more interesting. Furthermore, students show a high level of interest and feel more challenged and active when learning involves hands-on practice, experiments, the use of teaching aids or technology, and is conducted in a group work format. Thus, students indicate that the key to overcoming material difficulties is to implement a learning approach that is action-oriented, relevant to real life, and collaborative.

Based on the validity test results using Pearson's correlation analysis on 10 statement items (P01–P10), it was found that all items had a positive and significant relationship with the total instrument score with a significance value (Sig. 2-tailed) < 0.05. Items such as P05, P06, P08, P09, and P10 showed a very strong correlation with the total score, indicating that these items contributed significantly to the construct being measured. Meanwhile, items such as P02, P03, P04, and P07 showed moderate but still significant correlations, so were still declared valid. Item P01 had the lowest correlation value but was still significant. Overall, all instrument items were declared valid and suitable for use in measurements.

The reliability test results in Table 2 using Cronbach's Alpha statistics show a value of 0.775 for 10 items. This value indicates that the instrument has a good level of reliability and can be used. In general interpretation, a Cronbach's Alpha value above 0.70 is considered adequate, reflecting fairly good internal consistency between items on the scale. Thus, it can be concluded that the ten items used have shown mutually supportive correlations.

Table 2. Reliability test

Cronbach's Alpha	N of Items
0.775	10

When the glass bottle is filled with hot water, the air inside the bottle receives heat from the walls of the bottle. This heat causes the temperature of the air inside the bottle to rise, and according to the ideal gas law, the rise in temperature causes the air to expand. Because the mouth of the bottle is closed by a balloon, the expanding air enters the balloon, causing it to inflate. Ideal gas Equation (1).

$$PV = nRT \quad (1)$$

It is assumed that the pressure remains constant, so that when the final condition after filling with water occurs, a temperature difference remains ($\Delta \boldsymbol{T}$), so can be seen in Equation (2)

$$\frac{T_1}{P_1} = \frac{T_2}{P_2} \quad (2)$$

And in Equation (3)

$$P_2 = P_1 \frac{T_2}{T_2} \quad (3)$$

In the first law of thermodynamics can be seen in Equation (4)

$$\Delta U = Q - W \quad (4)$$

Since there is no change in temperature W = 0, so can be seen in Equation (5)

$$\Delta U = Q$$

$$nC_v \Delta T = Q \quad (5)$$

Therefore, the balloon will expand because Q, or the heat given to the gas in the bottle, increases the energy in the gas due to the temperature change, as shown in Figure 4 below.

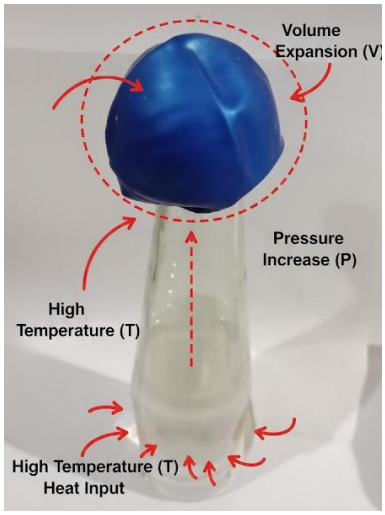


Figure 4. Ballons Kondition

The inflation of the balloon atop the glass bottle upon exposure to high-temperature water is a classical demonstration of the Ideal Gas Law, specifically highlighting the relationship between temperature and volume/pressure in a thermodynamic system. When the surrounding water is heated, heat energy is rapidly transferred through the glass wall and into the air trapped inside the bottle. This influx of energy elevates the absolute temperature of the gas. At the microscopic level, the increase in T corresponds directly to a significant rise in the average kinetic energy of the gas molecules, causing them to move faster and collide more frequently and forcefully with the container walls. Initially, since the volume of the rigid glass bottle is fixed, the primary effect is a substantial increase in pressure, according to Gay-Lussac's Law. This internal pressure quickly surpasses the external atmospheric pressure and the minor counter-pressure exerted by the uninflated rubber balloon. This resulting pressure differential exerts a net outward force on the flexible balloon surface. To restore equilibrium and satisfy the conditions of the Ideal Gas Law under the new, higher temperature, the system must increase its volume. Therefore, the balloon expands until the internal pressure decreases sufficiently to be balanced by the external pressure plus the elastic restoring force of the rubber. In summary, heat energy drives a pressure increase, which is ultimately accommodated by the expansion of the volume, demonstrating the direct thermodynamic link between thermal energy and the state variables of a gas.

The use of simulations is very influential in improving students' understanding and awareness of environmental issues (Hendrada et al., 2024). This is because students can directly observe the interactions that occur. As a result, students find it easier to learn the material. Students' interest in physics learning can be

enhanced through the use of contextual and engaging learning media, one of which is by integrating air expansion simulations. These simulations provide a realistic visualisation of abstract physics concepts (Ridwan et al., 2021). By observing firsthand how air expands due to changes in temperature or pressure through simulation, students find it easier to understand the concept, thereby fostering curiosity and interest in learning more (Costa et al., 2023). This simulation integratioN not only enrich the learning experience, but also creates a more interactive, meaningful, and enjoyable learning environment (Costa et al., 2023; Novita et al., 2025; Tazkya Mardatillah et al., 2025). This has had a direct impact on increasing students' interest in physics, which was previously considered difficult and boring. Continuous physics learning requires an approach that not only emphasises mastery of concepts but also fosters students' awareness of environmental issues (Karim et al., 2022; Moraes & Vianna, 2024). One approach that can be taken is to integrate air expansion simulation into the learning process (Wei et al., 2025; Francisco et al., 2025). Through this simulation, students can understand contextual principles, such as the relationship between pressure, volume, and air temperature, which are often directly related to environmental phenomena such as climate change and global warming (Rizki et al., 2024; Tadena & Salic-Hairulla, 2021). With a visual and interactive approach, students can more easily grasp the impact of human activities on energy balance and the atmosphere (Jauhari et al., 2024). This not only enhances understanding of physics concepts but also fosters the development of environmental awareness and the importance of responsible energy use (Khoiri et al., 2023; Zahro et al., 2025; Khan et al., 2025). Thus, the integration of air expansion simulation is an effective means of strengthening physics education that is relevant, meaningful, and oriented towards sustainability.

These studies underscore the important role that education plays in shaping public attitudes and behaviors toward environmental issues, making targeted educational interventions a valuable tool in the fight against the adverse consequences of climate change (Shen et al., 2025). Raising awareness about these issues through education is essential to promote sustainable urban development and environmental responsibility (Adaktylou, 2020). Integrating environmental topics into school curricula and professional development programs significantly increases knowledge and encourages environmentally responsible behavior (Saputri et al., 2025). This phenomenon-based teaching approach is highly effective because it encourages the development of critical thinking and independent observation while attempting to explain a real phenomenon, thereby maintaining motivation and activity in the learning process (Sunarti et al., 2025).

4. Conclusion

Integrating Air Expansion Simulation (AES) in Physics Learning to Enhance Sustainable Environmental Awareness with the help of simple simulations to increase students' interest in learning physics. Students prefer contextual learning and simple simulations because can be directly involved and make it an experience so that learning is not by memorization but by seeing the interactions that occur directly. This can be seen from the results of the questionnaire, where all questions received positive responses, meaning that this learning method can be used to increase students' interest in learning physics. In addition, based on the validity test results using Pearson's correlation, all instrument items are valid, and the reliability statistics of Cronbach's alpha are 0.775.

Author Contributions

Afif Jauhari: Conceptualization, Data curation, Formal analysis, Febiana Dinda Puspita: Funding acquisition, Investigation, Methodology, Project administration, Iqbal Ainur Rizki: Resources, Software, Sujito: Supervision, Validation, Visualization, Nurita Apridiana Lestari: Roles/Writing - original draft, Writing - review & editing. All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

No funding support was received.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

References

Adaktylou, N. (2020). Remote sensing as a tool for phenomenon-based teaching and learning at the elementary school level: A case study for the urban heat island effect. *International Journal of Educational Methodology, 6*(3), 517–532. https://doi.org/10.12973/ijem.6.3.517

Al-Kamzari, F., & Alias, N. (2025). A systematic literature review of project-based learning in secondary school physics: Theoretical foundations, design principles, and implementation strategies. *Humanities and Social Sciences Communications, 12*(1), 286. https://doi.org/10.1057/s41599-025-04579-4

BMKG. (2024). *Dampak perubahan iklim makin mengkhawatirkan*.

Costa, M. C., Ferreira, C. A. F., & Pinho, H. J. O. (2023). Physics of sound to raise awareness for sustainable development goals in the context of STEM hands-on activities. *Sustainability, 15*(4), 3676. https://doi.org/10.3390/su15043676

Embacher, F. (2025). An analytic model for climate and climate change suitable for advanced physics education. *European Journal of Physics, 46*(2), 025702. https://doi.org/10.1088/1361-6404/adab55

Fajar Nugroho, O., Ratna Juwita, S., & Febrianti, N. (2022). STEM education planning based on contextual issues sustainable development goals (SDGs). *Jurnal Ilmiah Pendidikan, 6*(2), 159–168. https://doi.org/10.33751/pedagonal.v6i2.5554

Francisco, S., Seixas, T. M., Cavadas, B., & Salgueiro da Silva, M. A. (2025). Deficit of environmental awareness among Angolan higher education physics teachers. *Physics Education, 60*(4), 045009. https://doi.org/10.1088/1361-6552/add2c3

Hariyono, E., Kurnia Prahanani, B., Aria Utama, J., & Mais, A. (2024). The science education students' understanding about global climate change issues in Indonesia. *KnE Social Sciences*. https://doi.org/10.18502/kss.v9i13.16004

Hendrada Putri, A. R., Usman, A., & Fashiha, H. M. (2024). Development of SESD (science education for sustainable development) based on student worksheet "climate action" social science content to construct critical thinking skills of elementary school students. *International Journal of Research and Review, 11*(6), 683–691. https://doi.org/10.52403/ijrr.20240674

Herlanti, Y., Nobira, S., Kuboki, Y., & Qumilaila, Q. (2025). Online lesson study design: Integrating environmental issues with science learning to enhance students' environmental literacy. *International Journal for Lesson & Learning Studies, 14*(1), 27–40. https://doi.org/10.1108/IJLLS-08-2024-0169

Hidaayatullaah, H. N., Hariyono, E., Hadiana, D., Fujii, H., & Satriawan, M. (2024). Exploring global dynamics of sustainable environmental sciences in climate change mitigation for sustainable development. *E3S Web of Conferences, 513,* 03014. https://doi.org/10.1051/e3sconf/202451303014

Indraj, & Warpa, V. (2024). Assessment of the seasonal trends of air pollution: A case study of Gurugram city, Haryana, India. *Journal of Air Pollution and Health, 9*(1), 29–40.

Jauhari, A., Puspita, F. D., Lestari, N. A., Deta, U. A., & Sujito. (2024). Solar photovoltaic as a potential renewable energy in environmentally friendly project-based physics learning. *Journal of Physics: Conference Series, 2900*(1), 012054. https://doi.org/10.1088/1742-6596/2900/1/012054

Karim, N., Othman, H., Zaini, Z. I., Rosli, Y., Wahab, M. I. A., Al Kanta, A. M., Omar, S., & Sahani, M. (2022). Climate change and environmental education: Stance from science teachers. *Sustainability, 14*(24), 16618. https://doi.org/10.3390/su142416618

Khan, F., Abbass, K., Qun, W., & Grebinevych, O. (2025). Moderating role of digital media on environmental awareness and environmental beliefs to shape farmers' behavioral intentions towards sustainable agricultural land conservation practices. *Journal of Environmental Management, 373*, 123745. https://doi.org/10.1016/j.jenvman.2024.123745

Khoiri, N., Roshayanti, F., & Widarti, R. (2023). Integration of STEAM and ESD: Improving the understanding of fluid concepts and creativity. *Journal of Education and E-Learning Research, 10*(3), 578–584. https://doi.org/10.20448/jeelr.v10i3.4987

Lee, H., Yoo, J., Choi, K., Kim, S.-W., Krajcik, J., Herman, B. C., & Zeidler, D. L. (2013). Socioscientific issues as a vehicle for promoting character and values for global citizens. International Journal of Science Education, 35(12), 2079–2113. https://doi.org/10.1080/09500693.2012.749546

Lestari, N. A., Hariyono, E., & Madlazim, M. (2024). Role of climate literacy in fostering climate change education, mitigation, and adaptation for sustainability: A bibliometric analysis. *AIP Conference Proceedings*. https://doi.org/10.1063/5.0215904

Maries, A., Li, Y., & Singh, C. (2025). Challenges faced by women and persons excluded because of their ethnicity and race in physics learning environments: Review of the literature and recommendations for departments and instructors. *Reports on Progress in Physics, 88*(1), 015901. https://doi.org/10.1088/1361-6633/ad91c4

Moraes, R. B. de, & Vianna, D. M. (2024). The articulation between the STS approach and environmental education for the contextualization of acoustics in physics teaching. *Journal of Physics: Conference Series, 2727*(1), 012019. https://doi.org/10.1088/1742-6596/2727/1/012019

Musengimana, T., Yadav, L. L., Uwamahoro, J., et al. (2025). Instructional strategies for enhancing students' problem-solving skills in physics: A systematic review. *Discover Education, 4,* 380. https://doi.org/10.1007/s44217-025-00733-x

Nelson, C. E. (2010). *Effective education for environmental literacy*. In Education for sustainability (pp. 117–129). Indiana University Press.

Novita, N., Andriani, R., Muliani, M., Makfirah, H., & Nur'azizah, N. (2025). Education for sustainable development (ESD) competency in physics learning assessment: Pre-service teachers' thinking skills based on ethno-socio-scientific content. *Jurnal Pendidikan IPA Indonesia, 14*(1). https://doi.org/10.15294/jpii.v14i1.15880

PISA. (2023). *PISA 2022 results: Factsheets Indonesia*. OECD.

Prahani, B. K., Dawana, I. R., & Sujarwanto. (2025). Exploring the potential of technology in physics education: Current research and innovation trends to support 21st century skills. *Perspectives of Science and Education, 73*(1), 349–361. https://doi.org/10.32744/pse.2025.1.23

Qiroah, I. F., & Lestari, N. A. (2024). Improving problem-solving skills using ESD integrated PBL models assisted with the greenhouse limas project. *Science Education and Application Journal, 6*(2), 138–154. https://doi.org/10.30736/seaj.v6i2.1097

Richter, K., & Kickmeier-Rust, M. (2025). Gamification in physics education: Play your way to better learning. *International Journal of Serious Games, 12*(1), 59–81. https://doi.org/10.17083/ijsg.v12i1.858

Ridwan, I. M., Kaniawati, I., Suhandi, A., Samsudin, A., & Rizal, R. (2021). Level of sustainability awareness: Where are the students' positions? *Journal of Physics: Conference Series, 1806*(1), 012135. https://doi.org/10.1088/1742-6596/1806/1/012135

Rizki, I. A., Hariyono, E., Suprapto, N., Dawana, I. R., & Shobah, N. (2024). Renewable energy learning project in physics classroom: Achieving education for sustainable development. *TEM Journal, 13*(2), 1452–1460. https://doi.org/10.18421/TEM132-59

Saputri, R., Wilujeng, I., Suyanta, S., Nurohman, S., Jumadi, J., Ilafi, M. M., & Purnama, A. Y. (2025). Improving problem-solving skills through the physics education technology-assisted problem-based learning model electronic student worksheets. *Revista Mexicana de Física E, 22*(2). https://doi.org/10.31349/RevMexFisE.22.020213

Shen, J., Zowada, C., Belova, N., Wei, R., & Chen, X. (2025). Integrating turbidimeter project work to promote sustainability education through interdisciplinary project-based learning. *Journal of Chemical Education, 102*(8), 3520–3527. https://doi.org/10.1021/acs.jchemed.5c00072

Shulla, K., Voigt, B. F., Cibian, S., Scandone, G., Martinez, E., Nelkovski, F., & Salehi, P. (2021). Effects of COVID-19 on the sustainable development goals (SDGs). *Discover sustainability, 2(*1), 15. https://doi.org/10.1007/s43621-021-00026-x

Siedlecki, S. L. (2020). Understanding descriptive research designs and methods. *Clinical Nurse Specialist, 34*(1), 8–12. https://doi.org/10.1097/NUR.0000000000000493

Solihah, P. A., Kaniawati, I., Samsudin, A., & Riandi, R. (2024). Prototype of greenhouse effect for improving problem-solving skills in science, technology, engineering, and mathematics (STEM)–education for sustainable development (ESD): Literature review, bibliometric, and experiment. *Indonesian Journal of Science and Technology, 9*(1), 163–190. https://doi.org/10.17509/ijost.v9i1.66773

Stouthart, T., Bayram, D., & van der Veen, J. (2025). Science teachers' views on student competences in education for sustainable development. *Journal of Research in Science Teaching. Advance online publication*. https://doi.org/10.1002/tea.22021

Sunarti, T., Suprapto, N., Hidaayatullaah, H. N., Suliyanah, S., Admoko, S., & Jauhariyah, M. N. R. (2025). Evaluating student responses to ethnophysics learning: Improving scientific literacy and problem-solving skills using a PLS-SEM approach. *Multidisciplinary Science Journal, 7*(10), 2025454. https://doi.org/10.31893/multiscience.2025454

Tadena, M. T. G., & Salic-Hairulla, M. A. (2021). Raising environmental awareness through local-based environmental education in STEM lessons. *Journal of Physics: Conference Series, 1835*(1), 012092. https://doi.org/10.1088/1742-6596/1835/1/012092

Tazkya Mardatillah, S., Karunia Shanty, S., Auliya, N., Lestari, N. A., & Rizki, I. A. (2025). Integrating technology and ethnophysics to support sustainable education and cultural preservation through traditional games of gasing and hula hoop in rotational physics learning. *Journal of Innovative Technology and Sustainability Education, 1*(1). https://doi.org/10.63230/jitse.1.1.38

Wei, N., Yang, F., Zhao, Y., Tian, H., Jin, Y., & Kumar, R. (2025). Environmentally friendly zein/ethylcellulose nanofiber air filtration materials with tunable hydrophobicity and high filtration efficiency. *International Journal of Biological Macromolecules, 290*, 139014. https://doi.org/10.1016/j.ijbiomac.2024.139014

Wibowo, F. C., Hasbey, H., Aziz, T. A., Darman, D. R., Kusuma, A. F. A. K., Ihsan, I., & Bunyami, M. A. H. (2025). Integrating artificial intelligence chatbot climate change with physics digital modules for student learning assistants. *Multidisciplinary Science Journal, 7*(12). https://doi.org/10.31893/multiscience.2025583

Winarto, W., Putri, A. F., Fahrezy, M., Arti, Y., Krsityaningrum, D. H., Rahayu, R., Ariyatun, A., & Hayu, W. (2025). How to improve students' problem-solving skills and environmental awareness: A study of the impact of worksheet problem-based learning on local potential of landfills Bantul region. *Multidisciplinary Science Journal, 7*(12). https://doi.org/10.31893/multiscience.2025564

Zahro, F., Lestari, N. A., & Roni, S. (2025). Effectiveness of physics learning with PBL model assisted by 3D webbook integrated with environmental learning in improving students' critical thinking skills. *Jurnal Penelitian Pendidikan Sains, 14*(2), 157–172. https://doi.org/10.26740/jpps.v14n2.p157-172

Zapp, M. (2021). The authority of science and the legitimacy of international organisations: OECD, UNESCO and World Bank in global education governance. *Compare: A Journal of Comparative and International Education, 51*(7), 1022–1041. https://doi.org/10.1080/03057925.2019.1702503