The Effect of the Problem Based Learning Model with Deep Learning Approach on Students' Sustainability Literacy in Renewable Energy Materials

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https://doi.org/10.17977/um065.v7.i3.2027.3

Article history
Submitted: 26 June 2026
Revised: 23 August 2026
Accepted: 27 August 2026
Published: 31 August 2026

Keywords
Deep learning approach
Problem based learning
Sustainability literacy

Abstract
Students' sustainability literacy remains relatively low due to teacher-centered learning and the limited implementation of contextual and meaningful learning approaches. At the same time, the demands of 21st-century education require instructional models that can enhance students' sustainability literacy. This study aimed to examine the effect of Problem Based Learning (PBL) integrated with a deep learning approach on students' sustainability literacy. A quantitative method with a quasi-experimental design was employed. The sample consisted of 31 students in the experimental class and 32 students in the control class. Data were collected using a four-tier diagnostic test, observation sheets, and a sustainability literacy questionnaire. The data were analyzed using the Kolmogorov–Smirnov normality test, Levene's homogeneity test, Independent Samples t-test, and N-gain analysis. The hypothesis test produced a Sig. (2-tailed) value of 0.000, which was below 0.05. This result indicates that the instructional intervention had a significant effect on students' sustainability literacy. The improvement in sustainability literacy in the experimental class was higher than that in the control class, with an average N-gain score of 0.7635 categorized as high, while the control class obtained an average N-gain score of 0.5945 categorized as moderate. Therefore, the findings indicate that the PBL model integrated with a deep learning approach significantly improves students' sustainability literacy on renewable energy materials.

1. Introduction

Education in the 21st century faces increasingly complex challenges due to technological, environmental, social, and global economic developments. These conditions require education not only to emphasize knowledge transfer but also to foster critical thinking, communication, collaboration, creativity and problem-solving skills relevant to real-life situations (Khahro & Javed, 2022). In response to these demands, the Sustainable Development Goals (SDGs) recognize education as a key mechanism for fostering sustainability awareness and developing the competencies necessary to support sustainable development through Education for Sustainable Development (ESD) (García-Feijoo et al., 2020; Glavič, 2020). Within this framework, sustainability literacy has emerged as a crucial educational outcome because it equips individuals with the knowledge, skills, values, and dispositions required to understand sustainability challenges and participate in efforts to address them (Décamps et al., 2017; Diamond & Irwin, 2013). Sustainability literacy encompasses three interrelated dimensions, namely sustainability knowledge, sustainability skills, and sustainability relevant values, which are interconnected in shaping students' sustainability awareness and behavior.

Science learning provides an important foundation for the development of sustainability literacy because it examines natural phenomena, environmental issues, and the relationship between humans and nature. One of the important goals of science education is to engage students in finding sustainable solutions to environmental problems (Kumar et al., 2024). Therefore, science learning should not only emphasize conceptual mastery but should also promote scientific thinking, investigative abilities, environmental responsibility, and sustainability-oriented behaviors (Kotkas et al., 2016). Despite its importance, previous studies indicate that students' sustainability literacy in Indonesia is still relatively low due to learning practices that remain theoretical and teacher-centered (Hamidah et al., 2024; Ihsan et al., 2025). Observations conducted in one public junior high school in Surakarta also revealed that science learning had not fully facilitated the development of sustainability literacy because classroom activities were still dominated by lectures and structured exercises,

ISSN: 2797-3174

limiting students' involvement in investigations, contextual problem-solving, and reflection on sustainability issues. In addition, teachers had not yet implemented comprehensive assessment instruments or optimally integrated sustainability issues into the learning process.

Problem Based Learning (PBL) has emerged as a promising instructional model for addressing these educational challenges. By using authentic problems as the foundation of learning, PBL encourages students to investigate issues, collaborate with peers, evaluate evidence, and formulate solutions to real-world issues (Arends, 2012; Marini et al., 2026). The characteristics of PBL, which emphasize authentic problems, investigation, and problem-solving, enable students to acquire knowledge, deepen conceptual understanding, and develop problem-solving and interpersonal skills through meaningful learning experiences (Valdez & Bungihan, 2019). Through these processes, PBL has the potential to develop sustainability literacy in the domains of knowledge, skills, and sustainability relevant values. To further optimize the implementation of PBL, a deep learning approach can be incorporated into the instructional process. Deep learning emphasizes meaningful engagement with learning content through critical reflection, contextual understanding, and active participation (Hattie & Donoghue, 2016). This approach is also aligned with Indonesian educational policy through the Regulation of the Ministry of Primary and Secondary Education Number 13 of 2025, which has begun implementing deep learning as a foundational framework for the national curriculum. Deep learning emphasizes the application of conceptual knowledge in real world contexts, enabling students to achieve deeper understanding and advanced cognitive skills while reducing reliance on memorization-based learning (Marblestone et al., 2016).

Although numerous studies have investigated the contribution of PBL to outcomes such as critical thinking, scientific literacy, student engagement, and problem-solving ability (Budhi & Suwarni, 2019; Marini et al., 2026). Other studies also indicate that students' sustainability literacy remains low due to learning practices that do not yet provide contextual and reflective learning experiences related to sustainability issues (Hamidah et al., 2024; Ihsan et al., 2025). However, empirical studies examining the integration of the PBL model with a deep learning approach to enhance sustainability literacy in science learning remain limited, particularly in renewable energy topics. Furthermore, the implementation of the deep learning approach in science education in Indonesia is still relatively new and has not been widely examined empirically. Therefore, there remains a research gap regarding the implementation of the PBL model integrated with a deep learning approach to improve students' sustainability literacy. Based on the issues and research gaps identified above, this study aims to analyze the effect of the Problem Based Learning (PBL) model integrated with a deep learning approach on students' sustainability literacy in renewable energy learning.

2. Method

This study employed a quantitative approach using a quasi-experimental design to analyze the effect of the Problem Based Learning (PBL) model integrated with a deep learning approach on students' sustainability literacy in renewable energy learning. A quasi-experimental design was adopted due to the practical limitations associated with controlling all external variables that could potentially influence the implementation of the intervention. The study utilized a pretest–posttest control group design involving one experimental group and one control group. Students in the experimental group participated in learning activities through the integration of PBL and a deep learning approach, whereas those in the control group received instruction through the Direct Instruction model combined with a scientific approach. To evaluate changes in sustainability literacy, both groups completed a pretest prior to the intervention and a posttest after the instructional treatment. The overall research procedure is illustrated in Figure 1.

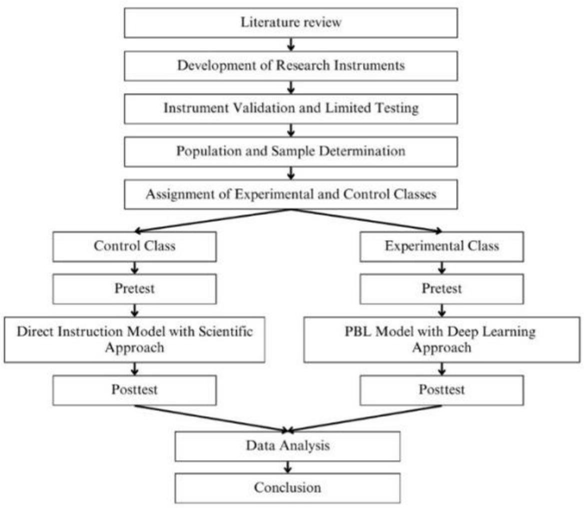

Figure 1. Research Procedure Flowchart

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The study was conducted at a public junior high school in Surakarta during the 2025/2026 academic year. The target population comprised all ninth-grade students enrolled in Classes IX A to IX E, with a total population of 159 students distributed across five classes. Two classes were selected as research samples through cluster random sampling, a technique considered suitable because the students had previously been organized into relatively homogeneous class groups. Class IX A was assigned as the experimental group, while Class IX B served as the control group. Prior to sample selection, the equivalence of the population was examined using students' Mid-Semester Summative Assessment scores in science. Statistical analyses included the Kolmogorov–Smirnov test to assess data normality and Levene's test to evaluate homogeneity. The findings indicated that all classes met the assumptions of normality and homogeneity, as evidenced by significance values exceeding 0.05. Furthermore, an Independent Samples t-test was conducted to verify the equivalence of the selected classes. The analysis yielded a significance value of 0.449, which exceeded the 0.05 threshold, indicating that the experimental and control groups possessed comparable initial academic abilities.

Data collection was conducted using three instruments: a sustainability literacy test, a questionnaire, and observation sheets. The test instrument employed a four-tier diagnostic test consisting of four levels: conceptual questions, confidence level of the answer, scientific reasoning, and confidence level of the reasoning. The instrument was used to measure students' sustainability literacy in the domains of sustainability knowledge, sustainability skills, and sustainability relevant values based on the framework proposed by Murray and Cotgrave (2007). The four-tier diagnostic test enabled a deeper assessment of students' conceptual understanding because it evaluated not only correct or incorrect answers but also scientific reasoning and confidence levels. Scoring was based on the combination of responses across the four tiers. Students who answered correctly on the first and third tiers and provided confident responses on the second and fourth tiers were categorized as having scientific conception and were assigned a score of 1, while other response combinations were assigned a score of 0 (Kaltakci-Gurel et al., 2017).

To complement the test results, a sustainability literacy questionnaire employing a four-point Likert scale was administered. The response categories included strongly agree, agree, disagree, and strongly disagree. The questionnaire and observation sheets were used to support the assessment of the sustainability skills and sustainability relevant values domains. All research instruments were first tested for content validity through expert judgment using Gregory's formula and were categorized as highly valid. Furthermore, the construct validity of the test and questionnaire instruments was analyzed using the Rasch model through the Winsteps application based on the criteria of Outfit Mean Square (MNSQ), Outfit Z-Standard (ZSTD), and Point Measure Correlation (Pt-Mean Corr). The analysis results indicated that all items in the pretest, posttest, and questionnaire instruments were valid. Instrument reliability was analyzed using Cronbach's Alpha, item reliability, and person reliability. The reliability test results showed that all instruments were categorized as highly reliable, with values greater than 0.70.

The research procedure began with a preparation stage, including the development of learning materials, preparation of research instruments, and validity and reliability testing. The implementation stage started with administering a pretest to both the experimental and control classes to determine students' initial sustainability literacy levels. Subsequently, the experimental class received instruction through the PBL model integrated with a deep learning approach on renewable energy material, while the control class was taught using the Direct Instruction model with a scientific approach. After the treatments were completed, both classes were given a posttest to determine changes in students' sustainability literacy after the learning process.

The collected data were analyzed using SPSS software. Prior to hypothesis testing, assumption testing was conducted through the Kolmogorov–Smirnov normality test and Levene's homogeneity test at a significance level of 0.05. Learning improvement was evaluated using the normalized gain (N-gain) test, which was used to determine the magnitude of students' progress from pretest to posttest. The N-gain scores were categorized into high, moderate, and low categories. Hypothesis testing was conducted using the Independent Samples t-test to determine the effect of the PBL model integrated with a deep learning approach on students' sustainability literacy by comparing the experimental and control classes. If the data did not meet the parametric assumptions, the nonparametric Mann–Whitney U test was employed.

3. Results and Discussion

3.1. Results

3.1.1. Sustainability Literacy Test Results

Sustainability literacy data were obtained using a four-tier diagnostic test consisting of 27 items. The analysis revealed a substantial increase in literacy scores in both groups following the instructional intervention. In the experimental class, the mean score improved from 21.62 on the pretest to 81.60 on the posttest. Similarly, the control class demonstrated progress, with the average score rising from 21.41 to 68.40. The average

ISSN: 2797-3174

sustainability literacy scores across the domains of sustainability knowledge, skills, and relevant values are presented in Figure 2.

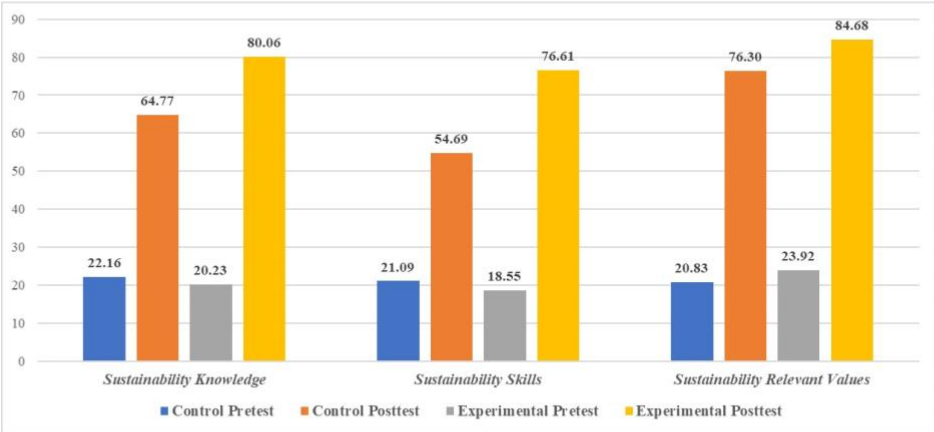

Figure 2. Average Sustainability Literacy Scores Across Domains

Based on Figure 2, gains were observed across all sustainability literacy domains in both groups. Nevertheless, students in the experimental class consistently achieved higher levels of improvement than those in the control class for each measured domain.

Prerequisite tests were conducted using the Kolmogorov–Smirnov normality test and Levene's homogeneity test at a significance level of 5% ($\alpha = 0.05$). The findings confirmed that both pretest and posttest scores were normally distributed, as indicated by significance values exceeding 0.05. The pretest data were homogeneous with a significance value of $0.110 > 0.05$, whereas the posttest data were not homogeneous because the significance value was $0.001 < 0.05$. Furthermore, hypothesis testing was conducted using the Independent Samples t-test based on the Equal Variance Not Assumed criterion because the posttest data were not homogeneous. The test results showed a significance value of $0.000 < 0.05$, indicating that H_0 was rejected and H_1 was accepted. These findings indicate that the implementation of the PBL model integrated with a deep learning approach had a significant effect on students' sustainability literacy.

In addition, the improvement in students' sustainability literacy was analyzed using the N-gain test. The analysis results showed that the experimental class obtained an average N-gain score of 0.7635, categorized as high, whereas the control class obtained an average N-gain score of 0.5945, categorized as moderate. Therefore, the improvement in sustainability literacy in the experimental class was higher than that in the control class.

3.1.2. Sustainability Literacy Observation Results

Observations were conducted to strengthen the sustainability literacy data in the domains of sustainability skills and sustainability relevant values during the learning activities. The observation results are presented in Table 1.

Table 1. Sustainability Literacy Observation Results

Domain	Experimental Class	Control Class
Sustainability Skills	81.85	52.73
Sustainability Relevant Values	86.16	77.47

Based on Table 1, students in the experimental class obtained higher observation scores than those in the control class in both assessed domains. These results suggest that the experimental class exhibited stronger sustainability skills and more positive sustainability relevant values during the learning process.

3.1.3. Sustainability Literacy Questionnaire Results

The sustainability literacy questionnaire data were used to support the measurement results in the domains of sustainability skills and sustainability relevant values. The average results of the students' sustainability literacy questionnaire are presented in Table 2.

Table 2. Sustainability Literacy Questionnaire Results

Domain	Experimental Class	Control Class
Sustainability Skills	83.74	70.83
Sustainability Relevant Values	84.51	73.18

ISSN: 2797-3174

Based on Table 2, students in the experimental class obtained higher questionnaire scores in both sustainability literacy domains than those in the control class. This pattern further supports the positive contribution of the intervention to the enhancement of sustainability skills and sustainability relevant values.

3.2. Discussion

The findings of this study demonstrate that the implementation of the Problem-Based Learning (PBL) model integrated with a deep learning approach had a significant positive effect on students' sustainability literacy in renewable energy learning. Students in the experimental class achieved significantly higher posttest scores and N-gain values than those in the control class, indicating that the combination of authentic problem-solving and meaningful learning experiences effectively promoted the development of sustainability literacy. These findings are discussed based on the three domains of sustainability literacy proposed by Murray and Cotgrave (2007): sustainability knowledge, sustainability skills, and sustainability relevant values.

The improvement in the sustainability knowledge domain can be attributed to the characteristics of PBL, which engage students in analyzing authentic environmental problems and constructing scientific understanding through investigation. Learning activities such as identifying renewable energy issues, conducting experiments, and discussing scientific evidence enabled students to connect theoretical concepts with real-world sustainability challenges. This finding is consistent with previous studies reporting that problem-based learning enhances conceptual understanding because students actively construct knowledge through inquiry and collaborative problem solving rather than passively receiving information (Amin et al., 2020; Argaw et al., 2017; Imandala et al., 2019; Lu et al., 2025). Furthermore, the deep learning approach strengthened conceptual mastery by encouraging students to learn meaningfully, reflect on their learning processes, and apply scientific concepts in new contexts (Hattie & Donoghue, 2016).

The sustainability skills domain also improved, although the increase was lower than that observed in the other two domains. This finding indicates that procedural and practical competencies require more sustained practice than conceptual understanding. Students developed these skills through experimental activities, collaborative investigations, data analysis, and the design of renewable energy solutions during the PBL process. These activities provided opportunities to apply scientific knowledge in practical situations while strengthening collaboration and problem-solving abilities. Similar findings have been reported by Pozuelo-muñoz et al. (2023) and Rauschenbach et al. (2018), who concluded that inquiry-based investigations and authentic problem-solving effectively promote sustainability-related skills because students repeatedly practice applying knowledge in real contexts. Moreover, Décamps et al. (2017) emphasized that sustainability skills require authentic experiences and repeated practice before knowledge can be transformed into concrete actions. In contrast, students in the control class mainly developed basic procedural skills through teacher guidance and structured exercises (Astra & Suganda, 2024; Dubinsky & Hamid, 2024).

The highest improvement occurred in the sustainability relevant values domain, indicating that PBL integrated with deep learning was particularly effective in fostering students' environmental awareness, responsibility, empathy, and commitment toward sustainability. Throughout the learning process, students reflected on the environmental consequences of energy consumption, discussed alternative renewable energy solutions, and evaluated the social implications of their decisions. Such learning experiences encouraged students to internalize sustainability values rather than merely understand sustainability concepts. This finding supports previous research suggesting that authentic environmental issues and collaborative reflection are effective strategies for developing pro-environmental values and responsible decision-making (Chen et al., 2022; Warners et al., 2026; Winarto et al., 2025). In comparison, teacher-centered instruction provides fewer opportunities for students to engage in authentic investigations and critical reflection related to environmental issues (Suhartono et al., 2019).

Overall, the findings indicate that Problem-Based Learning integrated with a deep learning approach is more effective than Direct Instruction with a scientific approach in improving students' sustainability literacy. The superiority of this learning model lies in its ability to simultaneously develop conceptual understanding, practical skills, and sustainability values through authentic, student-centered learning experiences. Unlike conventional instruction, which primarily emphasizes knowledge acquisition, PBL encourages students to investigate real problems, collaborate, reflect, and apply scientific knowledge in meaningful contexts, whereas Direct Instruction tends to provide fewer opportunities for students to construct knowledge independently and explore authentic sustainability issues (Budhi & Suwarni, 2019; Jong et al., 2024). Consequently, learning becomes more relevant to students' daily lives and better prepares them to address sustainability challenges in the future.

3.3. Implications

The results of this study suggest that integrating Problem Based Learning (PBL) with a deep learning approach offers a promising instructional strategy for enhancing students' sustainability literacy in science education, particularly in topics related to environmental sustainability and renewable energy. Through

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engagement in contextual problem-solving activities, experiments, collaborative discussions, presentations, and reflective practices, students were able to develop sustainability knowledge, skills, and relevant values more effectively. Furthermore, the findings provide additional empirical support for constructivist learning theories by demonstrating the effectiveness of active and meaningful learning experiences in fostering sustainability literacy.

3.4. Limitations

This study still has several limitations. The implementation of the PBL model required a longer learning duration, particularly during the investigation and experimental activities, which created challenges in managing classroom time effectively. Furthermore, because the study was conducted in only one junior high school and focused exclusively on renewable energy topics, the applicability of the findings to other educational contexts may be limited. Future investigations are encouraged to explore the integration of the PBL model and a deep learning approach across diverse subject areas, educational levels, and participant groups to provide broader empirical evidence.

4. Conclusion

The implementation of the Problem Based Learning (PBL) model integrated with a deep learning approach had a significant effect on improving students' sustainability literacy in renewable energy materials. Improvements were observed across all sustainability literacy domains including sustainability knowledge, skills, and relevant values. These outcomes suggest that learning activities involving authentic problem-solving, investigation, experimentation, collaboration, communication, and reflection provide meaningful opportunities for students to develop a deeper understanding of sustainability issues while strengthening sustainability-oriented competencies. Therefore, the integration of PBL and a deep learning approach can be considered a promising instructional alternative for science education, particularly in fostering students' sustainability literacy within the context of renewable energy and environmental sustainability.

Author Contributions

All authors were actively involved in the conceptualization, research design, implementation of the study, data analysis, and manuscript development. Each author critically reviewed the manuscript and provided approval for the final version before submission.

Funding

This research was funded by the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology, under Contract Number: 112/C3/DT.05.00/PL-MULTITAHUN LANJUTAN/2026 and LPPM UNS Multitahun Lanjutan Research Assignment Letter Number: 312.1/UN27.22/PT.01.03/2026.

Declaration of Conflicting Interests

The authors affirm that no financial, personal, or professional conflicts of interest influenced the conduct of this research or the preparation and publication of this manuscript.

Ethics and Consent Declarations

The research was conducted in compliance with established ethical standards. Permission to carry out the study was granted by the participating school, and informed consent was obtained from all participants prior to data collection. Throughout the research process, participant confidentiality, anonymity, and privacy were carefully maintained.

Data Availability

Research data supporting the conclusions of this study may be provided by the corresponding author upon reasonable request.

Declaration on AI Use

AI-based tools, including GPT and Gemini, were used solely to assist in improving the readability and language quality of the manuscript under the supervision of the authors. All scientific content, analyses, interpretations, and conclusions were entirely developed by the authors.

References

Amin, S., Utaya, S., Bachri, S., & Susilo, S. (2020). Effect of problem-based learning on critical thinking skills and environmental attitude. *Journal for the Education of Gifted Young Scientists, 8*(2), 743–755. https://doi.org/10.17478/jegys.650344

Arends, R. (2012). *Learning to teach* (9th ed.). McGraw-Hill.

ISSN: 2797-3174

Argaw, A. S., Haile, B. B., Ayalew, B. T., & Kuma, S. G. (2017). The effect of problem based learning (PBL) instruction on students' motivation and problem solving skills of physics. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(3), 857–871. https://doi.org/10.12973/eurasia.2017.00647a

Astra, I. M., & Suganda, Y. (2024). The effect of using worksheet based on a scientific approach assisted by scaffolding on high school student's cognitive learning outcomes on temperature and heat material. *Journal of Physics: Conference Series, 2866*(1), 012103. https://doi.org/10.1088/1742-6596/2866/1/012103

Budhi, W., & Suwarni, S. (2019). Effect of problem based learning on critical thinking ability on science. *Journal of Physics: Conference Series, 1175*(1), 012135. https://doi.org/10.1088/1742-6596/1175/1/012135

Chen, C., An, Q., Zheng, L., & Guan, C. (2022). Sustainability literacy: Assessment of knowingness, attitude and behavior regarding sustainable development among students in China. *Sustainability, 14*(9), 4886. https://doi.org/10.3390/su14094886

Décamps, A., Barbat, G., Carteron, J. C., Hands, V., & Parkes, C. (2017). Sulitest: A collaborative initiative to support and assess sustainability literacy in higher education. *The International Journal of Management Education, 15*(2), 138–152. https://doi.org/10.1016/j.ijme.2017.02.006

Diamond, S., & Irwin, B. (2013). Using e-learning for student sustainability literacy: Framework and review. *International Journal of Sustainability in Higher Education, 14*(4), 338–348. https://doi.org/10.1108/IJSHE-09-2011-0060

Dubinsky, J. M., & Hamid, A. A. (2024). The neuroscience of active learning and direct instruction. *Neuroscience & Biobehavioral Reviews, 163*, 105737. https://doi.org/10.1016/j.neubiorev.2024.105737

García-Feijoo, M., Eizaguirre, A., & Rica-Aspiunza, A. (2020). Systematic review of sustainable-development-goal deployment in business schools. *Sustainability, 12*(1), 1–19. https://doi.org/10.3390/su12010440

Glavič, P. (2020). Identifying key issues of education for sustainable development. *Sustainability, 12*(16), 6500. https://doi.org/10.3390/su12166500

Hamidah, N., Hidayat, T., Sriyati, S., & Hadibarata, T. (2024). Assessing sustainability literacy in green school through citizen science project on biodiversity learning. *Jurnal Inovasi Pendidikan IPA, 10*(2), 150–159. https://doi.org/10.21831/jipi.v10i2.71283

Hattie, J. A. C., & Donoghue, G. M. (2016). Learning strategies: A synthesis and conceptual model. *npj Science of Learning, 1*(1), 1–13. https://doi.org/10.1038/npjscilearn.2016.13

Ihsan, F., Himawanto, D. A., & Suharno, S. (2025). Mapping the landscape of sustainability literacy research in the Indonesian technical and vocational education. *Journal of Education and Learning (EduLearn), 19*(1), 350–361. https://doi.org/10.11591/edulearn.v19i1.21789

Imandala, I., Li, R., & Supriyadi, A. (2019). Analysis of problem-based learning models by typology of knowledge Pollock and Cruz (1999). *International Journal of Education and Learning, 1*(1), 1–11. https://doi.org/10.31763/ijele.v1i1.12

Jong, T., Lazonder, A. W., Chinn, C. A., Fischer, F., Gobert, J., Hmelo-Silver, C. E., … Zacharia, Z. C. (2024). Beyond inquiry or direct instruction: Pressing issues for designing impactful science learning opportunities. *Educational Research Review, 44*, 100623. https://doi.org/10.1016/j.edurev.2024.100623

Kaltakci-Gurel, D., Eryilmaz, A., & McDermott, L. C. (2017). Development and application of a four-tier test to assess pre-service physics teachers' misconceptions about geometrical optics. *Research in Science & Technological Education, 35*(2), 238–260. https://doi.org/10.1080/02635143.2017.1310094

Khahro, S. H., & Javed, Y. (2022). Key challenges in 21st century learning: A way forward towards sustainable higher educational institutions. *Sustainability, 14*(23), 16080. https://doi.org/10.3390/su142316080

Kotkas, T., Holbrook, J., & Rannikmäe, M. (2016). Identifying characteristics of science teaching/learning materials promoting students' intrinsic relevance. *Science Education International, 27*(2), 194–216. https://eric.ed.gov/?id=EJ1104649

Kumar, V., Kumar, S., & Singh, R. (2024). Environmental socio-scientific issues as contexts in developing scientific literacy in science education: A systematic literature review. *Social Sciences & Humanities Open, 9*, 100765. https://doi.org/10.1016/j.ssaho.2023.100765

Lu, L., Mustakim, S. S., & Muhamad, M. M. (2025). A meta-analysis of the effectiveness of problem-based learning on critical thinking. *European Journal of Educational Research, 14*(3), 789–804. https://doi.org/10.12973/eu-jer.14.3.789

Marblestone, A. H., Wayne, G., & Kording, K. P. (2016). Toward an integration of deep learning and neuroscience. *Frontiers in Computational Neuroscience, 10*, 94. https://doi.org/10.3389/fncom.2016.00094

Marini, A., Muawanah, U., & Marfu, A. (2026). Enhancing critical thinking through problem-based learning: The role of student engagement and technology for education sustainability in Indonesia. *Sustainable Futures, 11*, 101846. https://doi.org/10.1016/j.sftr.2026.101846

Murray, P. E., & Cotgrave, A. J. (2007). Sustainability literacy: The future paradigm for construction education? *Structural Survey, 25*(1), 7–23. https://doi.org/10.1108/02630800710740949

Pozuelo-Muñoz, J., Calvo-Zueco, E., Ester, S., & Cascarosa-Salillas, E. (2023). Science skills development through problem-based learning in secondary education. *Education Sciences, 13*(11), 1096. https://doi.org/10.3390/educsci13111096

Rauschenbach, I., Keddis, R., & Davis, D. (2018). Poster development and presentation to improve scientific inquiry and broaden effective scientific communication skills. *Journal of Microbiology & Biology Education, 19*(1), 1–9. https://doi.org/10.1128/jmbe.v19i1.1511

ISSN: 2797-3174

Suhartono, S., Degeng, I. N., Suyitno, I., & Sulton, S. (2019). A comparison study: Effects of the group investigation model and direct instruction model toward science concept understanding. *Jurnal Pendidikan IPA Indonesia, 8*(2), 185–192. https://doi.org/10.15294/jpii.v8i2.18135

Valdez, J. E., & Bungihan, M. E. (2019). Problem-based learning approach enhances the problem solving skills in chemistry of high school students. *Journal of Technology and Science Education, 9*(3), 282–294. https://doi.org/10.3926/jotse.631

Warners, M., Walker, S. E., Bruyere, B. L., Tamlyn, K., & Zarestky, J. (2026). Bridging nature, well-being, and sustainability through experiential learning in higher education. *Sustainability, 18*(1), 154. https://doi.org/10.3390/su18010154

Winarto, Putri, A. F., Fahrezy, M., Arti, Y., Kristyaningrum, D. H., Rahayu, R., Ariyatun, & Hayu, W. R. R. (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), 2025564. https://doi.org/10.31893/multiscience.2025564

ISSN: 2797-3174