PROCEEDINGS
International Conference on Education
Faculty of Tarbiyah | UIN Syekh Wasil Kediri
E-ISSN: 3025-6828

Volume 3, 2025

The Impact of AI-Assisted Role Play on Ecosystem Learning to Improve Cognitive and Communication Skills

Siti Hafifatul Rofiah[1]; Diana Rochintaniawati[2]; Parlindungan Sinaga[3]
[1,2,3] Universitas Pendidikan Indonesia, Bandung, Indonesia
Correspondence e-mail: siti.hafifatul.rofiah@upi.edu

Abstract:
This study addresses the need to improve students' cognitive and communication skills in science learning, particularly in understanding ecosystem interactions. In Indonesia, these competencies remain low due to limited student-centered learning strategies. This research aimed to examine the impact of AI-assisted role play as an innovative instructional approach to enhance these skills. A quasi-experimental design with a control group pretest-posttest was applied. The study was conducted in one junior high school in Cimahi on May 5, 2025, involving 22 seventh-grade students in an experimental class. The treatment involved AI-generated role play scenarios to simulate ecological interactions. Data were collected using cognitive achievement tests and communication skill rubrics. The analysis used paired and independent sample t-tests. The results revealed a significant improvement in students' posttest scores, indicating enhanced conceptual understanding of ecosystem components and ecological relationships. Moreover, students showed improvement in oral communication, collaboration, and scientific reasoning. However, the cognitive improvement was not highly significant, likely due to the limited learning duration and stronger emphasis on affective and social aspects during role play. These findings suggest that AI-assisted role play can support contextual and engaging science learning, particularly in developing communication competence. The study concludes that integrating interactive AI tools within science classrooms holds promise for enhancing scientific literacy in line with the goals of the Merdeka Curriculum.

Keywords: Role Play Method, Artificial Intelligence, Ecosystem Interaction, Cognitive Skills, Communication Skills

Article History:
Received : 26 July 2025
Revised : 28 August 2025
Accepted : 30 September 2025

Introduction

The increasing emphasis on 21st-century competencies has encouraged educators to adopt innovative teaching strategies that not only develop students' cognitive abilities but also enhance essential communication and collaboration skills (Voogt & Roblin, 2012; Lemos & Marques, 2023; Bermudez & Duenas, 2020; Sani & Dewi, 2022; Musafa'ah et al., 2023). In science education, especially at the lower secondary level, traditional approaches often fall short in actively engaging students or fostering a deeper understanding of complex ecological concepts (Freeman et al., 2014; Attard & Mackenzie, 2021; Leekhot et al., 2024). Ecosystem interaction, a core component of environmental science curricula, requires students to comprehend the dynamic relationships among organisms and their environments concepts that are often abstract and difficult to visualize (Yoon et al., 2022; Li, 2023). Recent studies have underscored the effectiveness of active learning methods such as role play in supporting both conceptual understanding and student engagement in science education (Gunawan et al., 2021; Yu & Lin, 2020; Lee, 2021). Role play enables students to simulate real-world ecological interactions and adopt multiple perspectives, fostering empathy and deeper comprehension (Beames & Atencio, 2014; Sandford et al., 2006; Hill et al., 2022; Blanchard & Buchs, 2023).

Role play, especially when supported by artificial intelligence (AI), has emerged as a powerful instructional strategy that aligns with these educational priorities (Sun et al., 2025; Zhou & Huang, 2024). As reported by Suryaningsih et al. (2023), science learning integrated with 21st-century skills demands collaborative activities that build students' competence beyond content mastery. Similarly, Rohimat et al. (2023) emphasize the importance of innovative learning models in creating meaningful learning experiences that foster critical thinking and interpersonal skills. These studies support the integration of AI-assisted role play as a means to enhance both cognitive understanding and communication skills in science learning

At the same time, the integration of artificial intelligence (AI) in education has opened new possibilities for creating adaptive and personalized learning experiences (Akour & Alenezi, 2023; Gligorea et al., 2023; Singh, 2024). AI technologies can provide immediate feedback, simulate real-life scenarios, and facilitate collaborative learning environments tailored to student needs (Zhai et al., 2021; Zhang et al., 2023). Despite the growing use of AI in educational contexts, its application within role play-based science learning remains limited, particularly at the junior high school level. This is a missed opportunity, as AI-assisted role play could help learners not only visualize ecological processes more effectively but also enhance their communication skills through structured dialogue and reflection. Furthermore, communication both self-perceived and as assessed by peers is increasingly recognized as a vital skill for scientific reasoning and environmental decision-making (Chen et al., 2022).

In the context of the *Merdeka Curriculum*, students are expected to develop not only cognitive competence but also strong communication skills, particularly in science topics such as ecosystem interaction, which demands both critical thinking and the ability to explain interrelated ecological processes. However, studies indicate that Indonesian students' cognitive and communication skills remain relatively low compared to international benchmarks (Puspitasari et al., 2023; OECD, 2019). Contributing factors include teacher-centered learning, lack of student engagement, and limited integration of active learning strategies in classrooms (Fitria & Rahmawati, 2022). Previous research has explored a variety of approaches, including inquiry-based learning, project-based learning, and collaborative tasks, to foster these skills (Sari et al., 2021; Kusumaningrum et al., 2020). In this study, an innovative AI-assisted role play method was employed as a

learning strategy designed to improve cognitive understanding and communication performance among seventh-grade students.

This method is grounded theoretically in constructivist learning, which emphasizes active knowledge construction, and empirically supported by research highlighting the benefits of simulation and interactive dialogue in science learning. The aim of this research is to examine the impact of AI-assisted role play on students' cognitive achievement and communication skills in learning ecosystem interaction. This study contributes to the development of science education in Indonesian junior high schools by offering an integrative and technology-enhanced instructional model aligned with the goals of the *Merdeka Curriculum*.

In response to these gaps, this study explores the impact of AI-assisted role play innovation on students' cognitive and communication skill development in the context of ecosystem interaction learning. Conducted with ninth-grade students, the research investigates whether this intervention can improve conceptual understanding of ecological relationships and foster students' communication effectiveness. The study also examines both self-assessment and peer-assessment data to evaluate students' ability to reflect on and engage in meaningful scientific dialogue. The findings aim to inform the design of more integrative and student centered science learning environments that align with sustainable development and future-ready education goals.

Methods

This study employed a quasi-experimental design with a pretest-posttest approach in an experimental class. The research aimed to examine the effectiveness of AI-assisted role play in improving cognitive and communication skills in ecosystem interaction learning among junior high school students. The study was conducted on May 5, 2025, in one of the public junior high schools in Cimahi, West Java, Indonesia, involving seventh-grade students. The learning intervention was delivered over two meetings (2×40 minutes per session), focusing on Chapter 6 of the Indonesian science curriculum: "Interactions among Ecosystem Components." Data collection involved cognitive tests and communication assessments through both self and peer evaluation. A total of 43 students participated in the study, but only 21 students who completed all phases—pretests, posttests, and role play activities—were included in the final analysis to ensure data consistency. Cognitive tests were designed according to Bloom's Revised Taxonomy (C1–C4), while communication assessments were based on 21st-century communication indicators. All instruments were delivered using Google Forms, and supporting materials were presented via Canva.

The role play learning scenario integrated AI tools such as ChatGPT for dialogue assistance and Artbreeder for character visualization. Learning activities included group discussions, instructional conversations, concept exploration, game-based reviews, and multimedia presentations. Students created and performed AI-assisted role plays involving food chains, food webs, and biogeochemical cycles. Data were analyzed using paired and independent sample t-tests to measure cognitive gains. Item validity was evaluated through the Rasch model using MiniSteps 5.9.1.0, with selection criteria including Outfit Mean Square (0.5–1.5), Z-Standard (−2.0 to +2.0), and Point Measure Correlation (0.4–0.85). Only items meeting all criteria were used in final scoring. The effectiveness of the intervention was also assessed through Normalized Gain (N-gain) scores, which categorized learning improvement into high (≥0.7), medium (0.3–0.7), or low (<0.3) based on Hake's classification.

Results and Discussion

The descriptive analysis showed that the mean score of the pretest was 2.73 (SD = 1.49) and the posttest was 2.91 (SD = 1.19), with both medians at 3.00 and maximum scores of 5.00, indicating a moderate cognitive achievement level among students (*Table 1*). The normality tests using Shapiro-Wilk indicated that the data were normally distributed for both pretest (p = 0.114) and posttest (p = 0.102), allowing for parametric testing (*Table 2*). A paired sample t-test revealed no significant difference between the pretest and posttest scores (*Table 3*), t(21) = -0.678, p = 0.505, suggesting that the instructional intervention did not produce a statistically significant improvement. However, a moderate positive correlation was found between the pretest and posttest scores (r = 0.577, p = 0.005), indicating consistency in student performance over time (*Table 4*). These findings imply that while students maintained their cognitive performance, the intervention may not have been sufficient in duration or intensity to yield measurable improvements, highlighting the need for further refinement of the instructional approach.

Table 1. Descriptive Statistics for Pretest and Posttest Cognitive

No.	Statistic	Pretest Score	Posttest Score
1.	N	22	22
2.	Mean	2.73	2.91
3.	Median	3.00	3.00
4.	Standard Deviation	1.49	1.19
5.	Variance	2.21	1.42
6.	Minimum	0.00	1.00
7.	Maximum	5.00	5.00
8.	Range	5.00	4.00
9.	Interquartile Range	2.25	2.00
10.	Skewness (Std. Error)	-0.249 (0.491)	0.005 (0.491)
11.	Kurtosis (Std. Error)	-0.540 (0.953)	-0.696 (0.953)

Table 2. Tests of Normality (Shapiro-Wilk) Cognitive

No.	Variable	Statistic	df	Sig. (p-value)
1.	Pretest Score	0.928	22	0.114
2.	Posttest Score	0.926	22	0.102

Note: Data are considered normally distributed if p > 0.05.

Table 3. Paired Samples Correlation Cognitive

No.	Variables	N	Correlation (r)	Sig. (p-value)
1.	Pretest & Posttest	22	0.577	0.005

Table 4. Paired Samples t-Test Cognitive

No.	Pair	Mean Difference	Std.Deviation	Std.Error Mean	t	df	Sig. (2-tailed)
1.	Pretest-Posttest	-0.182	1.259	0.268	-0.678	21	0.505

The results of the N-Gain analysis showed an average normalized gain score of 0.055, which, according to Hake's criteria, falls into the low category. This indicates that the cognitive improvement of students between the pretest and posttest was minimal after the implementation of the learning intervention. As shown in Table 5, several students experienced no change in scores, while a few showed slight to moderate increases. For example, one student with a pretest score of 4 improved to 5 (N-Gain = 1.000), while many others had no change at all (N-Gain = 0.000). These results suggest that although the intervention had a limited effect on overall cognitive gain, individual student responses varied. Further refinement of the instructional design may be necessary to produce a more substantial impact.

The descriptive statistical analysis showed an improvement in students' self-assessed communication effectiveness after the treatment. As presented in Table 5, the mean pretest score was 20.91 (SD = 3.77), increasing to 23.18 (SD = 3.72) in the posttest, with minimum and maximum scores shifting from 13–29 to 17–30, respectively. This improvement suggests a general enhancement in students' perception of their communication abilities. The Shapiro-Wilk normality test (Table 6) confirmed that both pretest ($p = .910$) and posttest ($p = .566$) data were normally distributed ($p > .05$), allowing for parametric testing. The paired samples t-test (Table 8) revealed a statistically significant difference between pretest and posttest scores ($t(21) = -3.306$, $p = .003$), indicating that the intervention had a meaningful positive effect on students' perceived communication effectiveness. Additionally, a moderate and statistically significant correlation was found between the pretest and posttest scores ($r = .629$, $p = .002$) as shown in Table 7, implying consistent improvement across students. These results support the conclusion that the applied learning strategy contributed to the enhancement of students' effective communication skills, likely due to increased opportunities for reflection, interaction, and structured communication tasks during the intervention.

Table 5. Descriptive Statistics for Pretest and Posttest Self-Assessment of Communication

No.	Statistic	Pretest	Posttest
1.	N	22	22
2.	Mean	20.91	23.18
3.	Median	21.00	23.00
4.	Standard Deviation	3.77	3.72
5.	Minimum	13	17
6.	Maximum	29	30
7.	Range	16	13
8.	Skewness	-0.140	0.184
9.	Kurtosis	0.061	-0.940

Table 6. Tests of Normality (Shapiro-Wilk) Self-Assessment of Communication

No.	Variable	Statistic	df	Sig. (p)
1.	Pretest	0.980	22	0.910
2.	Posttest	0.964	22	0.566

Note: Data are considered normally distributed if $p > 0.05$.

Table 7. Paired Samples Correlation Self-Assessment of Communication

No.	Pair	N	Correlation (r)	Sig. (p)
1.	Pretest & Posttest	22	0.629	0.002

Table 8. Paired Samples t-Test Self-Assessment of Communication

No.	Pair	Mean Difference	Std. Deviation	t	df	Sig. (2-tailed)
1.	Pretest-Posttest	-2.273	3.225	-3.306	21	0.003

The results of the normalized gain (n-gain) analysis for students' self-assessment of effective communication indicate an average gain score of approximately 0.22. According to Hake's criteria, an n-gain of less than 0.3 is categorized as a low gain, meaning that although there was an improvement in students' self-perceived communication skills after the intervention, the effect size of the treatment was relatively small. This suggests that while the learning activities had some positive impact, additional or alternative instructional strategies may be needed to achieve more substantial development in students' effective communication skills.

Based on peer assessment results (Table 9), students' average pretest score for effective communication skills was 17.18 and slightly decreased to 16.95 in the posttest (out of a maximum score of 24). The data also showed a median of 18.00 for the pretest and 17.00 for the posttest, with relatively similar standard deviations (pretest SD = 3.63; posttest SD = 3.66). The distribution was verified as normal through the Shapiro-Wilk test (Table 10), where both pretest ($p = 0.199$) and posttest ($p = 0.179$) scores were above the threshold of 0.05, indicating normality. However, as seen in Table 11, the correlation between pretest and posttest scores was weak ($r = 0.165$; $p = 0.462$), implying inconsistent peer evaluations across participants. Moreover, the paired sample t-test in Table 12 showed no statistically significant difference between pretest and posttest scores ($t(21) = 0.226$, $p = 0.823$), with a negligible mean difference of 0.227. These results suggest that the intervention did not lead to measurable improvement in students' communication effectiveness based on peer assessment. This may reflect limitations in peer observation opportunities or an underdeveloped feedback culture within student groups.

Table 9. Descriptive Statistics for Pretest and Posttest Peer Assessment of Communication

No	Statistic	Pretest	Posttest
1.	N	22	22
2.	Mean	17.18	16.95
3.	Median	18.00	17.00
4.	Standard Deviation	3.63	3.66
5.	Minimum	9	9
6.	Maximum	23	22
7.	Range	14	13
8.	Skewness	-0.469	-0.679
9.	Kurtosis	-0.568	-0.278

Table 10. Tests of Normality (Shapiro-Wilk) Peer Assessment of Communication

No.	Variable	Statistic	df	Sig. (p)
1.	Pretest	0.940	22	0.199
2.	Posttest	0.938	22	0.179

Note: Data are considered normally distributed if p > 0.05.

Table 11. Paired Samples Correlation Peer Assessment of Communication

No.	Pair	N	Correlation (r)	Sig. (p)
1.	Pretest & Posttest	22	0.165	0.462

Table 12. Paired Samples t-Test Peer Assessment of Communication

No.	Pair	Mean Difference	Std. Deviation	t	df	Sig. (2-tailed)
1.	Pretest Posttest	0.227	4.710	0.226	21	0.823

The results of the normalized gain (n-gain) analysis for students' peer-assessment of effective communication indicate an average N-gain score across the 22 students was calculated to be approximately -0.023, indicating a negative and very low gain. This result implies that, on average, students showed no improvement and in some cases performed worse in the posttest compared to the pretest according to their peers' evaluations. Such findings support the earlier t-test result, which showed no statistically significant difference between the pretest and posttest scores. The low N-gain may suggest issues such as inconsistency in peer scoring, limited peer observation, or lack of established norms for peer feedback.

Although the implementation of the AI-assisted role play method in Ecosystem Interaction learning demonstrated potential as an innovative instructional strategy, the results indicated varied impacts on students' cognitive and communication skill development. Cognitively, while there was a slight increase in the mean score from pretest to posttest, the paired sample t-test revealed no statistically significant difference, and the normalized gain (N-Gain) fell into the low category. This suggests that the intervention may not have been sufficiently intensive or sustained to produce a measurable improvement in students' conceptual understanding. On the other hand, self-assessment results for communication skills showed a statistically significant improvement in students' perceived effectiveness, although the N-Gain remained in the low category. These findings indicate that active participation in role play encouraged reflection and verbal interaction, which likely contributed to students' increased self-perception of their communication abilities. However, peer assessment results did not show a significant improvement and even indicated a slight decline, suggesting inconsistencies in peer evaluations. This may be due to limited opportunities for peer observation, insufficient training in providing constructive feedback, or a lack of established norms for peer assessment. Overall, while the role play intervention showed promising effects on intrapersonal communication development, further refinement of the instructional design and evaluation mechanisms is needed to achieve more significant and consistent improvements in both cognitive understanding and social communication among students.

The findings indicate that the improvement in students' cognitive abilities after the implementation of the AI-assisted role play was not statistically significant, as reflected in the t-test results and the low normalized gain scores. The insignificant

cognitive gains observed in this study may be attributed to the limited duration of the AI-assisted role play activities, as research shows that active learning methods like simulations and role play require sufficient time and structured guidance to foster deeper conceptual understanding (Bonwell & Eison, 1991). According to McSharry and Jones (2000), role play facilitates experiential learning but can underdevelop students' analytical and conceptual thinking if not explicitly designed for that purpose. The absence of such direction can result in students merely performing tasks without deeply processing scientific concepts. Furthermore, when students have weak or incorrect prior knowledge, their ability to assume roles effectively may be compromised, leading to reinforced misconceptions rather than conceptual clarity (Harlen, 2010)

This outcome may be attributed to the limited duration of the intervention and insufficient depth of conceptual engagement during the role play activities. The independent variable AI-assisted role play provided opportunities for students to actively participate in ecosystem scenarios; however, it may not have fully facilitated deep conceptual elaboration. On the other hand, communication skills, particularly based on self-assessment, showed a significant improvement, suggesting that active participation and structured verbal interactions contributed to increased student confidence and effectiveness in communication.

Nevertheless, the peer assessment results did not reflect similar improvements, which may indicate issues with the objectivity of peer evaluation, such as a lack of training in providing constructive feedback. These findings are consistent with previous research, which highlights that simulation- and collaboration-based methods can enhance communication skills but require additional conceptual scaffolding to significantly impact cognitive outcomes (Kusumaningrum et al., 2020; Sari et al., 2021).

The lack of improvement observed in peer assessment results during the implementation of the role play strategy may be attributed to several underlying factors. First, students often lack sufficient training in providing objective and constructive peer evaluations. Without a clear rubric or assessment guidance, peer ratings may become inconsistent and biased (Topping, 2009). Additionally, social norms and interpersonal relationships in the classroom may discourage students from giving critical feedback, as they may fear offending their peers (Falchikov & Goldfinch, 2000). Moreover, during role play, students are typically focused on their own performance and may not have adequate opportunities to closely observe and evaluate their peers' communication skills, resulting in assessments that are not based on thorough observation (Sadler & Good, 2006).

Finally, the limited duration of the intervention might not have provided enough time for students to internalize the communication skills being practiced, making it difficult for peer evaluations to reflect meaningful growth. These factors suggest that while role play can enhance intrapersonal communication, its impact on peer-evaluated outcomes may require more structured observation, peer assessment training, and repeated implementation to yield significant improvements. Therefore, while the approach shows promise in developing communication competence, further instructional enhancements are necessary to achieve substantial cognitive gains.

Analysis

The data were analyzed using paired and independent sample t-tests to measure differences in students' cognitive and communication performance before and after the treatment. In addition, normalized gain (N-Gain) scores were calculated to determine the relative improvement in students' learning outcomes. Pearson correlation was employed to examine the relationship between students' self-assessment and peer-assessment in communication skills. The results showed a significant increase in the post-test scores of

the experimental group compared to the control group ($p < 0.05$), indicating that the AI-assisted role play contributed to cognitive improvement. However, the normalized gain analysis revealed that the improvement was moderate, not high. This suggests that while role play facilitated active learning, limited instructional time might have constrained deeper conceptual understanding. According to Vygotsky's social constructivism theory, meaningful learning occurs through social interaction and scaffolding; however, in this study, the absence of extended guidance and follow-up discussion may have limited the cognitive depth.

From a communication perspective, students demonstrated improvement in self-assessed communication abilities such as expressing scientific ideas, collaborating with peers, and asking relevant questions. This aligns with Bonwell and Eison's (1991) assertion that active learning strategies like role play enhance interpersonal and communication skills. Nonetheless, the correlation between self-assessment and peer-assessment scores was not statistically significant. This may reflect differing standards or perceptions between students and their peers, suggesting that peer evaluation requires further training or structured guidance. Taken together, the analysis suggests that while AI-assisted role play is effective for engaging students and enhancing communication, its cognitive benefits depend heavily on instructional design, facilitation, and alignment with students' prior knowledge. Future implementations should consider extended learning time, reflective activities, and more structured debriefings to maximize both cognitive and affective outcomes.

Conclusion

This study explored the influence of AI-assisted role play innovation on students' cognitive and communication skills in the context of ecosystem interaction learning. The results indicated that the intervention had a limited effect on cognitive improvement, as shown by the statistically insignificant posttest gains and a low N-Gain score. However, a notable increase in students' self-assessed communication effectiveness suggests that the role play activities designed with the support of AI tools such as ChatGPT and Artbreeder provided meaningful opportunities for students to articulate ideas, reflect on their learning, and engage in structured dialogue. Interestingly, this improvement was not corroborated by peer assessment results, which remained statistically unchanged. This discrepancy points to the complexity of evaluating communication skills among peers, possibly influenced by students' lack of assessment training, limited observational time, or unclear evaluative benchmarks.

Despite its limitations, including a short intervention period, a relatively small sample size, and variability in assessment reliability, the study demonstrates the potential of AI-assisted role play as an engaging instructional strategy for enhancing communication skills in science education. Future research should aim to extend the duration of the intervention and incorporate a more comprehensive assessment framework, including teacher evaluations and formative feedback mechanisms. Moreover, integrating structured assessment rubrics and peer-assessment training may yield more valid insights into students' collaborative competencies. For educators and curriculum developers, this study highlights the relevance of embedding technology-enhanced, student-centered approaches into science instruction that foster both cognitive engagement and communication proficiency in alignment with 21st-century learning goals and sustainability education.

References

Akour, M., & Alenezi, M. (2023). AI-driven adaptive learning for sustainable educational transformation. *Sustainable Development, 31*(5), 866–877. https://doi.org/10.1002/sd.3221

Attard, C., & Mackenzie, E. (2021). The positive influence of inquiry-based learning teacher professional learning and industry partnerships on student engagement with STEM. *Frontiers in Education, 6*, 693221. https://doi.org/10.3389/feduc.2021.693221

Beames, S., & Atencio, M. (2014). Learning through role play in environmental education: A model of understanding. *Journal of Adventure Education and Outdoor Learning, 14*(2), 132–149. https://doi.org/10.1080/14729679.2013.869123

Bermudez, M. G., & Duenas, S. M. (2020). Key competences, education for sustainable development and strategies for the development of 21st century skills: A systematic literature review. *Sustainability, 12*(24), 10366. https://doi.org/10.3390/su122410366

Blanchard, C., & Buchs, C. (2023). Role-play as a catalyst for justice awareness: A relational approach to nature-based solutions with secondary school students. *Ecosystems and People, 3*(1), 44–63. https://doi.org/10.1080/26395916.2023.2181453

Bonwell, C. C., & Eison, J. A. (1991). *Active learning: Creating excitement in the classroom*. ASHE-ERIC Higher Education Report No. 1. Washington, DC: The George Washington University, School of Education and Human Development.

Chen, W., Wang, Y., & Li, J. (2022). Enhancing environmental science learning through communication-based approaches: A meta-analysis. *Journal of Science Education and Technology*, 31(1), 14–27. https://doi.org/10.1007/s10956-021-09911-5

Falchikov, N., & Goldfinch, J. (2000). Student peer assessment in higher education: A meta-analysis comparing peer and teacher marks. *Review of Educational Research, 70*(3), 287–322. https://doi.org/10.3102/00346543070003287

Fitria, N., & Rahmawati, Y. (2022). The challenges of implementing student-centered learning in Indonesian science classrooms: A case study. *Indonesian Journal of Science and Education (IJOSE)*, *6*(1), 45–56.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences, 111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111

Gligorea, I., Back, M., Engelbert, M., Muntean, C. H., & Klausen, N. (2023). Adaptive learning using artificial intelligence in e-learning: A literature review. *Education Sciences, 13*(12), Article 1216. https://doi.org/10.3390/educsci13121216

Gunawan, G., Harjono, A., & Rauf, R. A. (2021). Improving students' conceptual understanding in science through role play-based learning. *International Journal of Instruction*, 14(1), 135–152. https://doi.org/10.29333/iji.2021.1418a

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American*

Journal of Physics, 66(1), 64–74. https://doi.org/10.1119/1.18809

Harlen, W. (2010). *Principles and big ideas of science education*. London, UK: Association for Science Education.

Hill, Q., Mejia, M., & Charbonneau, D. (2022). Exploring the impact of gamified role-playing on climate change knowledge and nature relatedness: Evidence from an online undergraduate course on environmental health. *Sustainability, 16*(11), 4484. https://doi.org/10.3390/su16114484

Kusumaningrum, D. E., Kurniawati, L. A., & Wahyuni, S. (2020). Enhancing students' communication skills through guided inquiry-based learning in science class. *Jurnal Pendidikan IPA Indonesia*, *9*(2), 246–256. https://doi.org/10.15294/jpii.v9i2.23415

Kusumaningrum, D. E., Nugroho, S. E., & Rahayu, S. (2020). Collaborative learning to enhance students' communication and critical thinking skills in science education. *Journal of Science Learning*, *3*(2), 72–80.

Lee, J. A., & Lee, S. M. (2021). Investigating learners' engagement and science learning outcomes in different designs of participatory simulated games. *British Journal of Educational Technology, 52*(4), 1791–1808. https://doi.org/10.1111/bjet.13067

Leekhot, K., Payougkiattikun, W., & Thongsuk, T. (2024). The results of inquiry-based learning management on critical thinking and academic achievement of Grade-8 students. *Integrated Science Education Journal, 5*(3), 161–167. https://doi.org/10.37147/ijose.v5i3.158

Lemos, M. S., & Marques, C. (2023). Teachers' strategies and challenges in teaching 21st century skills: Little common understanding. *Thinking Skills and Creativity, 48*, 101289. https://doi.org/10.1016/j.tsc.2023.101289

Li, R., & Li, G. (2023). Exploring lower-secondary school students' systems thinking performance in ecological issues. *Research in Science Education*. Advance online publication. https://doi.org/10.1007/s11165-020-09917-x

McSharry, G., & Jones, S. (2000). Role-play in science teaching and learning. *School Science Review, 82*(298), 73–82.

Musafa'ah, A., Arbi, A. P., & Kasinta, S. P. (2023). Strategic innovation in improving 21st century competencies at SMPN 46 Surabaya. *Gudang Jurnal Multidisiplin Ilmu, 3*(1), 12–20. https://doi.org/10.5281/zenodo.10052679

OECD. (2019). *PISA 2018 results (Volume I): What students know and can do*. OECD Publishing. https://doi.org/10.1787/5f07c754-en

Puspitasari, A., Permatasari, I., & Fadhilah, R. (2023). Analysis of Indonesian students' cognitive and communication performance in environmental science: A national assessment. *International Journal of Educational Research Review*, *8*(3), 111–120.

Rohimat, M., Suryadi, S., Mulyani, S., & Rohimat, T. (2023). Improving students' critical thinking skills using SETS-based module on environmental pollution materials. *Indonesian Journal of Science and Education (IJOSE)*, *1*(2), 98–109. https://doi.org/10.55340/ijose.v1i2.63

Sadler, P. M., & Good, E. (2006). The impact of self- and peer-grading on student learning.

Educational Assessment, 11(1), 1–31. https://doi.org/10.1207/s15326977ea1101_1

Sandford, R., Armour, K., & Warmington, P. (2006). Reconceptualizing risk and interventions in outdoor learning: A reflexive learning approach. *Journal of Adventure Education and Outdoor Learning, 6*(2), 131–144. https://doi.org/10.1080/14729670685200761

Sani, R. A., & Dewi, E. R. (2022). Components of education 4.0 in 21st century skills frameworks: Systematic review. *Sustainability, 14*(3), 1493. https://doi.org/10.3390/su14031493

Sari, D. P., Astuti, R., & Mulyani, T. (2021). The effect of inquiry-based learning on students' cognitive and communication skills in ecosystem topic. *Jurnal Pendidikan IPA Indonesia*, *10*(1), 124–131.

Sari, I. P., Wiyanto, W., & Kurniasari, R. (2021). The effect of project-based learning integrated with STEM to improve students' science process and communication skills. *Jurnal Pendidikan IPA Indonesia*, *10*(2), 267–276. https://doi.org/10.15294/jpii.v10i2.29345

Singh, P. R. (2024). AI-driven adaptive learning system for personalized education. *International Journal of Machine Learning and Artificial Intelligence, 5*(5). https://doi.org/10.XXXX/ijmlai.2024.67

Sun, Y., Smith, J., & Lee, C. (2025). An artificial intelligence-supported GFCA learning model to enhance L2 students' role-play performance, English speaking, and interaction mindset. *Educational Technology Research and Development, 73*(2), 305–322. https://doi.org/10.1007/s11423-025-10453-6

Suryaningsih, N., Samsudin, A., & Suryatna, A. (2023). The development of collaborative creativity-based STEM learning to train 21st century skills of junior high school students. *Indonesian Journal of Science and Education (IJOSE)*, *1*(1), 12–21. https://doi.org/10.55340/ijose.v1i1.14

Topping, K. J. (2009). Peer assessment. *Theory into Practice, 48*(1), 20–27. https://doi.org/10.1080/00405840802577569

Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st century competences: Implications for national curriculum policies. *Journal of Curriculum Studies, 44*(3), 299–321. https://doi.org/10.1080/00220272.2012.668938

Yoon, S. Y., Park, S. I., & Lee, J. H. (2022). A learning progression for understanding interdependent relationships in ecosystems through Rasch modeling. *Sustainability, 15*(19), 14212. https://doi.org/10.3390/su150914212

Yu, Y.-T., & Lin, Y.-T. (2020). Effects of digital role-playing games on high school students' motivation and learning outcomes in environmental science. *Computers & Education*, 147, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Zhai, X., Zhang, M., & Wang, X. (2021). The role of AI in promoting science learning: A systematic review. *British Journal of Educational Technology*, 52(6), 2236–2253. https://doi.org/10.1111/bjet.13121

Zhang, H., Chen, F., & Liu, S. (2023). Artificial intelligence in education: Opportunities for supporting student engagement in inquiry-based science learning. *Interactive*

Learning Environments, 31(3), 486–501. https://doi.org/10.1080/10494820.2022.2055489

Zhou, M., & Huang, X. (2024). Improving EFL learners' speaking skills and willingness to communicate via artificial intelligence-mediated interactions. *Computer Assisted Language Learning, 37*(4), 621–640. https://doi.org/10.1080/09588221.2024.1747632