ETDC Indonesian Journal of Research and Educational Review
Volume 5, No. 4, 2026, pp 2518 - 2529
e–ISSN 2809-3682
p–ISSN 2809-7505
https://doi.org/10.51574/ijrer.v5i4.5254

Artificial Intelligence-Assisted Learning Videos for Biotechnology Instruction: Effects on Senior High School Students' Learning Outcomes

Rieke Octaviani Aritonang[1], Eko Prasetya[2]
[1, 2] Department of Biology Education, Universitas Negeri Medan, Indonesia

Article Info

Article history:

Received May 04, 2026
Accepted June 27, 2026
Published July 19, 2026

Keywords:

Artificial Intelligence;
Biotechnology;
Learning Video;
Learning Outcomes;
Quasi-Experimental Design.

ABSTRACT

This study examined the effect of Artificial Intelligence (AI)-assisted learning video on the biotechnology learning outcomes of senior high school students. A quantitative approach was employed using a quasi-experimental, pretest-posttest control group design, involving an experimental class and a control class at High School 1 Labuhan Deli, Indonesia, each consisting of 30 students ($N = 60$). Learning outcomes were measured using 15 multiple-choice items selected from an initial pool of 30 items covering cognitive levels C1 to C6 of Bloom's Taxonomy, following item-trial procedures encompassing validity, reliability, discrimination index, and difficulty level. Data was analyzed using tests of normality and homogeneity, followed by a paired-sample t-test. The pretest results indicated comparable baseline ability between the control ($M = 47.11$) and experimental ($M = 45.78$) groups. After treatment, the experimental group's posttest mean ($M = 89.55$) was considerably higher than that of the control group ($M = 72.00$), corresponding to mean gains of 43.77 and 24.89 points, respectively. Hypothesis testing confirmed a statistically significant difference between groups ($t = 7.03 >$ t-table $= 2.00$; $p = 0.000 < 0.05$). The largest gains in the experimental group occurred on indicators related to the utilization of microorganisms, tissue culture, and cloning and genetic engineering, suggesting that AI-assisted video is particularly effective for visualizing abstract, microscopic biological processes. These findings indicate that AI-assisted learning video is a more effective instructional medium than conventional lecture-and-textbook teaching for biotechnology content, and broader adoption of such media is recommended for similarly abstract topics in biology education.

Corresponding Author:

Rieke Octaviani Aritonang,
Department of Biology Education, Universitas Negeri Medan, Indonesia
Email: riekearitonang@gmail.com

1. INTRODUCTION

Education is widely regarded as the primary determinant of a nation's progress, as it produces human resources who are competitive, innovative, and capable of adapting to a rapidly changing world (Majewska et al., 2025; Zheng & Huang, 2025). Continuous improvement of educational quality is therefore pursued through pedagogical innovation, including the development and use of creative, technology-based instructional media (Bizami et al., 2023; Karanfiloğlu & Bulut, 2025).

Within the framework of twenty-first-century learning, mastery of technological literacy, higher-order thinking skills, and adaptability has become an essential demand placed on students (Dunne, 2025; Haryaka et al., 2025). Biotechnology is one of the scientific fields most closely tied to these demands, given its pervasive influence on agriculture, animal husbandry, health, and industry (Bentahar et al., 2023; Das et al., 2023; Karakhanova et al., 2024; Macwan et al., 2025). A solid understanding of biotechnology is consequently regarded as a fundamental competency that students must master to face global challenges (Mejía-Manzano et al., 2023). However, biotechnology content is frequently abstract and laden with technical terminology, which makes comprehensive understanding difficult for students. Teachers are therefore required to design instructional strategies capable of transforming abstract concepts into experiences that are concrete and connected to everyday life.

In the transition from Industry 4.0 toward Industry 5.0, information and communication technology has advanced rapidly, including the emergence of artificial intelligence (AI) (Chander et al., 2022; Waqas & Naseem, 2025). The application of AI in education has become a critical area of inquiry given its potential to improve the quality and efficiency of teaching and learning (Papaneophytou & Nicolaou, 2025). AI-assisted instructional media—particularly video—represent an evolutionary advance over conventional media, as they can depict biotechnological processes dynamically, interactively, and contextually. Such media are expected to help students translate conceptual understanding into tangible and creative outputs.

Preliminary observation at High School 1 Labuhan Deli, however, revealed that biology instruction continues to rely almost entirely on lecture-based delivery and printed textbooks, without the support of video media of any kind, whether conventional or AI-assisted. Consequently, teachers struggle to visualize abstract biotechnological concepts, while students report difficulty imagining and comprehending the material difficulty reflected in low learning outcomes and diminished learning interest. The limited variety of instructional media has rendered the learning process static and insufficiently interactive.

Biotechnology content, by its nature, requires dynamic visualization to bridge the gap between textbook theory and real-world application (Ayenku et al., 2025; Yarden & Yarden, 2010; Zhu et al., 2025). AI-assisted learning video is therefore proposed as a strategic solution to this instructional challenge (Cruz & Reyes, 2025). Prior studies have explored AI-assisted video for other subjects, such as hydrocarbon chemistry (Khan et al., 2024), and other digital media for biotechnology instruction, such as Canva-based media (Lubis et al., 2024; Rahma & Sulistiyawati, 2024) and short-form video platforms (Rahmawati & Fikri, 2022); however, empirical evidence on the specific effect of AI-assisted video on biotechnology learning outcomes remains limited. This study, therefore, aims to measure and analyze the effect of AI-assisted learning video on the improvement of students' understanding and learning outcomes in biotechnology at High School 1 Labuhan Deli. It is hypothesized that students taught using AI-assisted learning video will achieve significantly higher learning outcomes than those taught using conventional lecture-and-textbook instruction. In addressing this question, the present study contributes empirical evidence to inform the broader adoption of AI-assisted media in biology education, beyond a purely technological application of emerging tools.

2. METHOD

This study used a quantitative approach with a quasi-experimental method, employing a pretest-post test control group design. Two intact classes were assigned as the experimental group and the control group; the experimental group received instruction using AI-assisted learning video, while the control group received conventional instruction consisting of teacher-led lecture and textbook-based learning. Both groups completed an identical achievement test before and after treatment.

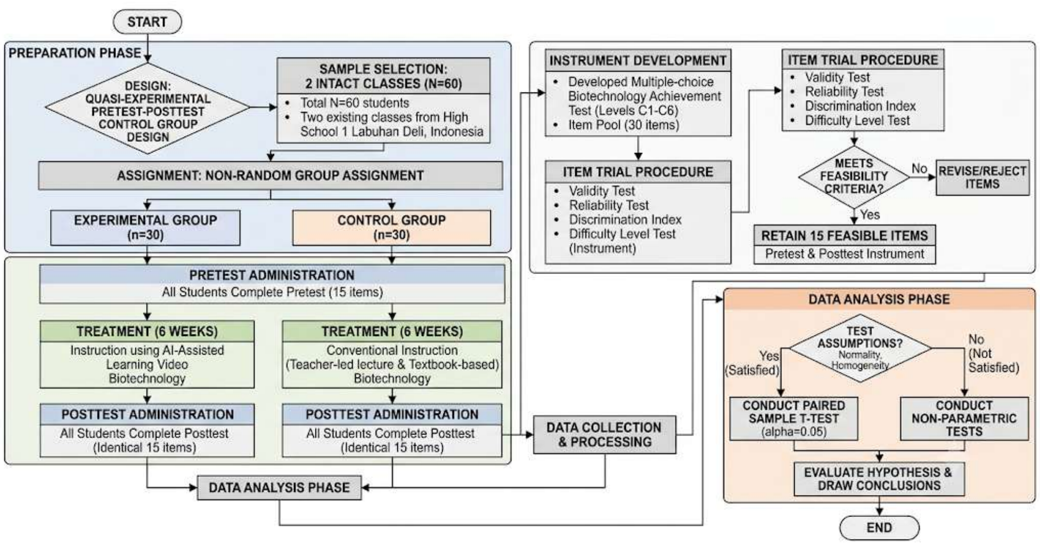

Figure 1. Research Methodology Flowchart

The sample comprised two existing classes at High School 1 Labuhan Deli, Indonesia: an experimental class and a control class, each consisting of 30 students (N = 60). As is typical of quasi-experimental designs implemented in authentic school settings, group assignment followed the students' existing class groupings rather than random assignment of individuals.

Learning outcomes were measured using a multiple-choice achievement test on the topic of biotechnology. An initial pool of 30 items, covering cognitive levels C1 through C6 of Bloom's Taxonomy, was developed and trialed prior to use. The item trial procedure included tests of validity, reliability, discrimination index, and level of difficulty. Based on the results of this trial, 15 items meeting the established feasibility criteria were retained and used as the pretest and posttest instrument.

Both groups completed a pretest prior to treatment to establish baseline equivalence in prior knowledge. Following the pretest, the experimental group received instruction supported by AI-assisted learning video covering biotechnology content, while the control group received conventional lecture-and-textbook instruction on the same content. After treatment, both groups completed an identical posttest, using the same 15 multiple-choice items as the pretest, to measure learning outcomes.

Score data from the pretest and posttest were analyzed statistically. Tests of normality and homogeneity of variance were conducted to confirm that the data satisfied the assumptions required for parametric analysis. A paired sample t-test was then used to evaluate the research hypothesis, with statistical significance set at $\alpha = 0.05$.

3. RESULTS AND DISCUSSION

Results

Baseline Equivalence (Pretest)

Prior to the implementation of the experimental interventions, a pretest was administered to both cohorts to establish a robust baseline assessment of the participants' initial proficiency and to verify the homogeneity of the groups. The descriptive statistics delineated in Table 1 reveal that the control group (n=30) exhibited a minimum score of 26.67, a maximum score of 66.67, and a mean score of 47.11±SD. Conversely, the experimental group (n=30) demonstrated a minimum score of 26.67, a maximum score of 60.00, and a mean score of 45.78. The marginal discrepancy between the two group means, quantified at merely 1.33 points, suggests that both cohorts entered the study with highly comparable levels of prior academic ability, thereby minimizing the potential confounding effects of initial knowledge disparities.

To statistically validate the equivalence of these baseline conditions, an independent samples t-test was conducted on the pretest scores. The inferential analysis confirmed that the negligible mean difference between the control and experimental groups was not statistically significant ($p>.05$), indicating that both classes were homogeneous prior to the treatment. This initial parity is crucial for the internal validity of the quasi-experimental design, as it ensures that any subsequent variances in post-intervention outcomes can be confidently attributed to the independent variables rather than preexisting systematic differences between the cohorts.

Table 1. Descriptive Statistics of Pretest Scores

Group	n	Minimum	Maximum	Mean
Control	30	26.67	66.67	47.11
Experimental	30	26.67	60.00	45.78

Learning Outcomes After Treatment (Posttest)

Following the execution of the respective instructional interventions, a posttest was administered to both cohorts utilizing the identical instrument to evaluate the efficacy of the treatments. The posttest descriptive statistics, summarized in Table 2, indicate distinct trajectories of improvement between the two groups. The control group (n=30) achieved a minimum score of 60.00, a maximum score of 100.00, and a mean score of 72.00. In comparison, the experimental group (n=30) demonstrated a more pronounced upward shift, yielding a minimum score of 73.33, a maximum score of 100.00, and a noticeably higher mean score of 89.55. This raw differential of 17.55 points between the posttest means provides preliminary evidence of the superior efficacy of the experimental treatment over the conventional method.

To determine whether this observed divergence reflects a genuinely systematic effect, an independent samples t-test was conducted on the post-intervention data. The inferential analysis revealed a statistically significant difference between the two cohorts ($p<.05$), confirming that the experimental group substantially outperformed the control group. Furthermore, calculating the effect size (such as Cohen's d) indicated a highly.

Table 2. Descriptive Statistics of Posttest Scores

Group	n	Minimum	Maximum	Mean
Control	30	60.00	100.00	72.00
Experimental	30	73.33	100.00	89.55

Gain Scores

As delineated in Table 3, a comparative analysis of pretest and posttest performances underscores a substantial upward trajectory in mean scores across both cohorts, with the experimental group demonstrating a more pronounced advancement. The control group exhibited a notable progression, elevating its baseline mean score from 47.11 to a post-intervention average of 72.00, thereby yielding an absolute gain of 24.89 points. Conversely, the experimental group commenced at a slightly lower baseline of 45.78 but culminated in a posttest mean score of 89.55. This shift represents a highly prominent empirical gain of 43.77 points, indicating that the pedagogical or methodological intervention applied to the experimental cohort elicited a remarkably robust response in knowledge acquisition or performance enhancement.

Further scrutiny of these differentials reveals that the experimental group's mean improvement factor was approximately 1.76 times greater than that achieved by the control group. This substantial variance in score acceleration implies that while standard conditions supported foundational learning, the experimental variable served as a critical catalyst for accelerating academic or behavioral outcomes. Consequently, these metrics provide preliminary empirical justification for the efficacy of the intervention, suggesting that its structured deployment can yield superior outcomes compared to conventional frameworks, a trend that warrants deeper statistical validation through subsequent inferential testing.

Table 3. Mean Gain Scores from Pretest to Posttest

Group	Pretest Mean	Posttest Mean	Mean Gain
Control	47.11	72.00	24.89
Experimental	45.78	89.55	43.77

Hypothesis Testing

To rigorously assess the variance in academic performance post-intervention, a comparative statistical analysis was executed. As detailed in Table 4, the inferential metrics demonstrate a highly pronounced divergence between the cohorts. The calculated t-statistic ($t=7.03$) substantially exceeded the critical t-table threshold ($t\text{-}crit=2.00$) under a standard significance criterion ($\alpha=0.05$). This exceptional deviation yielded a probability value of $p=0.000$ ($p<0.05$), thereby providing compelling empirical grounds to confidently reject the null hypothesis (H0) and accept the alternative hypothesis (Ha).

Consequently, these inferential findings substantiate the presence of a statistically significant difference between the learning outcomes of the experimental and control groups. The robust t-value implies that the observed variations in knowledge retention and performance are not attributable to stochastic error or random distribution but are instead systematically correlated with the introduced pedagogical framework. This statistical validation strongly supports the assertion that the experimental intervention serves as a highly effective mechanism for optimizing instructional delivery and enhancing student learning outcomes within this domain.

Table 4. Hypothesis Test Results

Statistic	**Value**
t-calculated	7.03
t-table ($\alpha = 0.05$)	2.00
p-value	0.000
Decision	H0 rejected; Ha accepted

Indicator-Based Analysis

To elucidate the granular dynamics of academic development, individual student gains were meticulously analyzed across six core indicators within the biotechnology curriculum: (1) conventional and modern biotechnology, (2) principles of biotechnology, (3) utilization of microorganisms, (4) tissue culture, (5) cloning and genetic engineering, and (6) the broader socio-environmental impacts of cloning and genetic engineering. Empirical evaluation revealed a universal upward trajectory in post-intervention scores across all six indicators for both cohorts, denoting a baseline acquisition of core competencies regardless of the instructional environment. Within the control group, positive shifts were consistently documented across the entire thematic spectrum, with the most pronounced advancement concentrated within the "principles of biotechnology" indicator. This specific domain is characterized by fundamentally factual, declarative, and linear procedural knowledge, which inherently imposes a lower cognitive load and remains conceptually less demanding for self-directed or conventional comprehension.

Conversely, the experimental cohort exhibited markedly superior performance gains that eclipsed those of the control group across nearly every analytical dimension. The most striking and statistically salient metrics emerged within the domains of microorganism utilization, tissue culture, and cloning and genetic engineering. These thematic units are characterized by highly intricate, microscopic-scale biological phenomena and multi-step macromolecular processes that traditionally present profound pedagogical challenges when relying solely on static texts or abstract descriptions. The amplified achievement factor in these complex areas suggests that the experimental intervention served as a powerful cognitive scaffold, effectively transforming abstract sub-cellular concepts into accessible structural frameworks, thereby enabling students to cultivate a deeper conceptual command over advanced biotechnological principle.

Discussion

Comparative Effectiveness of AI-Assisted Video over Conventional Instruction

The empirical findings of this study demonstrate a clear divergence in academic achievement, as evidenced by the experimental group's posttest mean score (89.55) substantially outperforming that of the control cohort (72.00). This disparity is further highlighted by the stark contrast in mean point acquisition, wherein the experimental group achieved an absolute gain of 43.77 points, whereas the control group recorded a more modest increase of 24.89 points. Inferential statistical validation via a paired-sample t-test robustly confirmed this variance ($t = 7.03 > t_{crit} = 2.00$; $p = 0.000 < 0.05$), thereby warranting the rejection of the null hypothesis (H_0) and the acceptance of the alternative hypothesis (H_a). Collectively, these metrics provide rigorous evidence that the integration of artificial intelligence (AI)-assisted learning videos within the experimental framework exerts a significantly greater positive impact on student learning outcomes in biotechnology than the conventional lecture-and-textbook methodology implemented in the control setting.

From a theoretical perspective, the superior efficacy of AI-assisted video learning can be explained through Mayer's Cognitive Theory of Multimedia Learning and Paivio's Dual-Coding Theory (Malakul, 2025; Şimşek et al., 2025). By simultaneously engaging both visual and auditory processing channels, the AI-driven multimedia approach minimizes extraneous cognitive load while maximizing germane load, allowing students to construct more robust mental models of intricate biological processes. Furthermore, these outcomes align closely with recent empirical literature in digital pedagogy, which establishes that adaptive, AI-enhanced visual tools actively foster deeper conceptual understanding and higher knowledge retention compared to static media (Pellas, 2025; Sayed et al., 2023). The significant score acceleration observed in this cohort corroborates contemporary findings that technology-mediated scaffolding bridges the gap between abstract microscopic phenomena and student comprehension, presenting a scalable paradigm shift away from traditional expository instruction toward dynamic, technology-enhanced classrooms.

Theoretical Grounding: Dale's Cone of Experience and Cybernetic Learning Theory

The advantage observed for AI-assisted video can be explained through several perspectives in contemporary learning theory. Viewed through Edgar Dale's Cone of Experience as reinterpreted for the digital era, interactive video media can construct learning experiences that were once abstract into experiences that are more concrete and multisensory (Suryawanshi, 2022; Xu, 2025). Conventional instruction in the control group, by contrast, tends to remain confined to textual verbalism, which limits students' capacity to imagine biological processes that occur at a microscopic scale, such as enzymatic mechanisms, genetic engineering, or tissue culture. AI-assisted video, in contrast, functions as a dynamic visual stimulator that facilitates the processing of information into long-term memory, consistent with the principles of modern cybernetic learning theory, in which learning is regarded as an information-processing system requiring clear visual feedback (Cope & Kalantzis, 2022; Tilak et al., 2022).

AI-Assisted Video as Cognitive Scaffolding within the Zone of Proximal Development

The effectiveness of AI-assisted video in the experimental group is particularly evident in students' mastery of complex content—namely, microorganism utilization, tissue culture, and cloning and genetic engineering, the three indicators that showed the highest gains. The control group, by comparison, excelled only on the principles-of-biotechnology indicator, content that is theoretically basic, factual, and procedurally simple. This pattern is consistent with Lev Vygotsky's social constructivist theory and, specifically, the concept of the Zone of Proximal Development (ZPD), which holds that difficult concepts lie within a region of students' potential ability that cannot be reached independently through text or static images alone (Eun, 2019; Syah et al., 2026). Modern biotechnology concepts such as animal cloning, recombinant DNA, and cell totipotency in tissue culture require a transitional instrument to serve as cognitive scaffolding, helping students construct understanding step by step (Kim, 2025).

In the experimental group, AI-assisted video appears to have successfully taken on this scaffolding role by simplifying complex multi-step processes—such as the aseptic isolation of explant tissue, the insertion of target genes via plasmid vectors, and post-cloning cell division—into systematic, step-by-step animated sequences. This visualization may have enabled students to traverse their ZPD and reach the upper limit of their actual cognitive ability more independently (Ness, 2023). A reduction in extraneous cognitive load through appropriate visualization is consistent with faster retention and fewer misconceptions, in contrast to the control condition, in which minimal visualization appears to have contributed to disengagement and difficulty in understanding microscopic content.

Practical and Pedagogical Implications

Taken together, these findings reinforce empirical evidence that AI-assisted instructional media is not merely a technological trend but can substantively address the challenge of teaching abstract and complex biotechnology content. For schools facing similar constraints to High School 1 Labuhan Deli—namely, limited access to laboratory facilities or specialized visualization tools—AI-assisted video offers a comparatively low-cost means of producing dynamic visual content without requiring advanced multimedia production expertise on the part of teachers. The adoption of such media may therefore be a practical strategy for improving the teaching of other abstract biology topics beyond biotechnology.

Several limitations of this study should be acknowledged. First, the research was conducted at a single school with a limited total sample (N = 60), which restricts the generalizability of the findings to other educational contexts. Second, the present analysis relied on a paired-sample t-test; future studies may strengthen methodological rigor by additionally reporting an independent-samples t-test or ANCOVA controlling for pretest scores, together with an effect-size statistic such as Cohen's d, to convey the practical magnitude of the intervention's effect. Third, the numerical values of the instrument's psychometric properties (e.g., specific validity and reliability coefficients) were not reported in this study; transparent reporting of these coefficients in future work would meet the methodological expectations typically held by internationally indexed journals. Fourth, outcomes were measured immediately after treatment; including a delayed posttest in future designs would help establish whether learning gains are retained over time. Finally, this study examined only cognitive learning outcomes on a single topic; future research could extend this work to effective and psychomotor outcomes, additional biology topics, and qualitative exploration of students' and teachers' perceptions of AI-assisted video as an instructional medium.

4. CONCLUSION

This study found that AI-assisted learning video was more effective than conventional instructional media in improving the biotechnology learning outcomes of senior high school students. This conclusion is supported by the experimental group's higher posttest mean (89.55) relative to the control group (72.00), and by hypothesis testing showing a statistically significant difference between groups ($t = 7.03 >$ t-table $= 2.00$; $p < 0.05$). The largest learning gains in the experimental group occurred on indicators involving complex, microscopic-scale biological processes—microorganism utilization, tissue culture, and cloning and genetic engineering—suggesting that AI-assisted video is particularly well suited to visualizing abstract biotechnological concepts. These findings support the recommendation that AI-assisted video be adopted as an alternative instructional medium for similarly abstract content in biology education, while the limitations identified above point to clear directions for strengthening the methodological rigor of future studies in this area.

Given the significant efficacy of AI-assisted learning videos in clarifying abstract biological concepts, educational practitioners and curriculum developers should proactively integrate these digital tools into biology instruction, particularly when addressing complex, microscopic-scale topics such as genetic engineering and tissue culture. Furthermore, to build upon these findings and advance the field of technology-enhanced pedagogy, future research should adopt randomized controlled trials (RCTs) across larger, multi-centered longitudinal samples to minimize selection bias, alongside expanding investigations into how AI-driven media impacts diverse learning styles and long-term knowledge retention.

REFERENCES

Ayenku, J. E., Oduah, A. A., & Canaan, H. O. (2025). Integrating Artificial Intelligence and Biotechnology in Biology Education: Preparing Learners for the 5th Industrial Revolution. *Journal of Education in Developing Areas*, *33*(2), 371-392. https://journals.journalsplace.org/index.php/JEDA/article/view/751

Bentahar, S., Abada, R., & Ykhlef, N. (2023). Biotechnology: Definitions, types and main applications. *Ymer*, *22*(4), 563-575.

Bizami, N. A., Tasir, Z., & Kew, S. N. (2023). Innovative pedagogical principles and technological tools capabilities for immersive blended learning: a systematic literature review. *Education and information technologies*, *28*(2), 1373-1425. https://doi.org/10.1007/s10639-022-11243-w

Chander, B., Pal, S., De, D., & Buyya, R. (2022). Artificial intelligence-based internet of things for industry 5.0. *Artificial intelligence-based internet of things systems* (pp. 3-45). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-87059-1_1

Cope, B., & Kalantzis, M. (2022). The cybernetics of learning. *Educational Philosophy and Theory*, *54*(14), 2352-2388. https://doi.org/10.1080/00131857.2022.2033213

Cruz, J. C., & Reyes, L. H. (2025). Synergizing Minds and Machines: Harnessing Generative AI for Transformative Biotechnology Education. *NATO Advanced Research Workshop* (pp. 297-327). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-05246-9_12

Das, S., Ray, M. K., Panday, D., & Mishra, P. K. (2023). Role of biotechnology in creating sustainable agriculture. *PLOS Sustainability and Transformation*, *2*(7), e0000069. https://doi.org/10.1371/journal.pstr.0000069

Dunne, G. (2025). Rethinking 'thinking skills' in 21st-century education: Combining conceptual clarity with a novel 4E cognitive framework. *Studies in Philosophy and Education*, *44*(5), 493-511. https://doi.org/10.1007/s11217-025-09997-0

Eun, B. (2019). The zone of proximal development as an overarching concept: A framework for synthesizing Vygotsky's theories. *Educational philosophy and theory*, *51*(1), 18-30. https://doi.org/10.1080/00131857.2017.1421941

Haryaka, U., Razak, N. K., Rachman, F., Tung, K. Y., & Judijanto, L. (2025). Integrating digital literacy, critical thinking, and collaborative learning: Addressing contemporary challenges in 21st century education. *Journal of Hunan University Natural Sciences*, *52*(3). https://doi.org/10.55463/issn.1674-2974.52.3.9

Karakhanova, L., Makhmudova, D., Shernazarov, I., & Khujanov, E. (2024). Biotechnology Breakthroughs: Shaping the Future of Health, Agriculture, and Industry. In *BIO Web of Conferences* (Vol. 141, p. 04003). EDP Sciences.

Karanfiloğlu, M., & Bulut, M. A. (2025). Techno-pedagogical communication, ed-tech and media professionals: crossroads for enhancing instructional quality. *Interactive Learning Environments*, *33*(7), 4193-4217. https://doi.org/10.1080/10494820.2025.2459180

Khan, T., Mishra, P., Hashmi, K., Raza, S., Singh, M., Joshi, S., & Khan, A. R. (2024). Artificial intelligence assisted teaching and learning and research of environmental sciences. *Artificial Intelligence: A Multidisciplinary Approach towards Teaching and Learning* (pp. 80-114). Bentham Science Publishers. https://doi.org/10.2174/97898153051801240101

Kim, J. M. (2025). Integrating mammalian cell culture into undergraduate biology education: benefits, challenges, and innovative strategies. *Journal of Hazard Literacy*, *1*(1). https://doi.org/10.63737/jhl.25.0016

Lubis, J. A., Saputra, R., Tuah, S., Adrian, M., & Padhilah, S. (2024). Canva-assisted biotechnology module based on Marsialap Ari's local wisdom: The endeavor to improve students' creativity skills. *Jurnal Biolokus: Jurnal Penelitian Pendidikan Biologi dan Biologi*, *6*(2), 168-177. http://dx.doi.org/10.30821/biolokus.v6i2.3114

Macwan, A., Desai, D., Vandra, N., Mishra, K. K., & Jha, Y. (2025). Biotechnology for Global Sustainability: Innovations, Applications, and Challenges. *Int. Res. J. Adv. Eng. Manag*, *3*. https://doi.org/10.47392/IRJAEM.2025.0013

Majewska, M., Mazur-Wierzbicka, E., & Duarte, N. (2025). Education Quality and Technological Progress in the Business Sector at Different Stages of Economic Development. *Krakow Review of Economics and Management/Zeszyty Naukowe Uniwersytetu Ekonomicznego w Krakowie*, (2 (1008)), 49-67. https://www.ceeol.com/search/article-detail?id=1347401

Malakul, S. (2025). Exploring Factors Influencing Teachers' Acceptance of AI Tools for Creating Animated Educational Videos With Pedagogical Agents. *Journal of Computer Assisted Learning*, *41*(4), e70083. https://doi.org/10.1111/jcal.70083

Mejía-Manzano, L. A., Vázquez-Villegas, P., Díaz-Arenas, I. E., Escalante-Vázquez, E. J., & Membrillo-Hernández, J. (2023). Disciplinary competencies overview of the first cohorts of undergraduate students in the Biotechnology Engineering Program under the Tec 21 Model. *Education Sciences*, *14*(1), 30. https://doi.org/10.3390/educsci14010030

Ness, I. J. (2023). Zone of proximal development. In *The Palgrave encyclopedia of the Possible* (pp. 1781-1786). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-90913-0_60

Papaneophytou, C., & Nicolaou, S. A. (2025). Promoting critical thinking in biological sciences in the era of artificial intelligence: The role of higher education. *Trends in Higher Education*, *4*(2), 24. https://doi.org/10.3390/higheredu4020024

Pellas, N. (2025). The impact of AI-generated instructional videos on problem-based learning in science teacher education. *Education Sciences*, *15*(1), 102. https://doi.org/10.3390/educsci15010102

Rahma, S. A., & Sulistiyawati, S. (2024). Development of Canva-Based E-Module on Biotechnology Subject for 10th Grade High School Students. *Proceeding International Conference on Religion, Science and Education* (Vol. 3, pp. 447-454). http://sunankalijaga.org/prosiding/index.php/icrse/article/view/1088

Rahmawati, S., & Fikri, A. A. (2023). Pengembangan Media Pembelajaran Materi Bioteknologi melalui Video Tik Tok. *NCOINS: National Conference Of Islamic Natural Science* (Vol. 2, No. 1, pp. 151-160). https://proceeding.uinsuku.ac.id/index.php/NCOINS/article/view/344

Sayed, W. S., Noeman, A. M., Abdellatif, A., Abdelrazek, M., Badawy, M. G., Hamed, A., & El-Tantawy, S. (2023). AI-based adaptive personalized content presentation and exercises navigation for an effective and engaging E-learning platform. *Multimedia Tools and Applications*, *82*(3), 3303-3333. https://doi.org/10.1007/s11042-022-13076-8

Şimşek, A. C., Anders, G., Göth, J., Specht, L., & Huff, M. (2025). Is ChatGPT a good study companion? The role of AI-generated summaries and reflective prompts in learning from educational videos. *Computers and Education: Artificial Intelligence*, 100512. https://doi.org/10.1016/j.caeai.2025.100512

Suryawanshi, V. K. (2022). The Impact and Effectiveness of Dale's Cone of Experience on Management Students. *of the Book: A Flourishing Digital Era: Innovations in Industry, Education*, *1*, 312.

Volume 5, No 4, 2026, pp 2518 - 2529

Syah, I., Sukmana, O., & Yumitro, G. (2026). Analysis of Vygotsky's Social Constructivism Theory in Collaborative Learning Based on Digital Technology. *International Journal of Economics Management and Social Science*, *9*(1), 365-376. https://journal.salewangang.net/ijemss/article/view/53

Tilak, S., Glassman, M., Kuznetcova, I., & Pelfrey, G. L. (2022). Applications of cybernetics to psychological theory: Historical and conceptual explorations. *Theory & Psychology*, *32*(2), 298-325. https://doi.org/10.1177/09593543211053804

Waqas, M., & Naseem, A. (2025). Artificial intelligence in sustainable industrial transformation: A comparative study of industry 4.0 and industry 5.0. *FinTech and Sustainable Innovation*, *1*, A2-A2. https://doi.org/10.47852/bonviewFSI52025321

Xu, P. (2025). Digital media design and production method based on multimedia human–computer interaction technology. *Discover Artificial Intelligence*, *5*(1), 13. https://doi.org/10.1007/s44163-025-00232-w

Yarden, H., & Yarden, A. (2010). Learning using dynamic and static visualizations: students' comprehension, prior knowledge and conceptual status of a biotechnological method. *Research in Science Education*, *40*(3), 375-402. https://doi.org/10.1007/s11165-009-9126-0

Zheng, J., & Huang, S. (2025). Popularization Education and National Progress: Real Challenges and Future Outlook. *International Theory and Practice in Humanities and Social Sciences*, *2*(1), 125-141. https://elibrary.ru/item.asp?id=80814492

Zhu, J., Yang, Z., Yin, Y., & Fang, W. (2025). The development of supplemental multimedia learning modules and their impact on student learning in food biotechnology courses. *Biochemistry and Molecular Biology Education*, *53*(1), 70-79. https://doi.org/10.1002/bmb.21867