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Development of a STEAM–ESD-Based AI Chatbot to Enhance Students' Scientific Literacy in Biotechnology Learning

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Abstract
The integration of artificial intelligence in science learning is a strategic need to address the challenges of scientific literacy and sustainable education. This study aims to develop and test the effectiveness of a STEAM-ESD (Science, Technology, Engineering, Arts, and Mathematics-Education for Sustainable Development)-based chatbot in improving students' scientific literacy in biotechnology learning. The study used a research and development (R&D) design with the ADDIE model which includes the stages of analysis, design, development, implementation, and evaluation. The product developed is an AI chatbot "BIOTEKS" along with learning support tools. The research subjects were 12th grade high school students. Data were collected through expert validation sheets and science literacy tests, then analyzed descriptively and inferentially using Rasch analysis, N-gain, and the Mann-Whitney U test. The results showed that all learning tools had a very high level of validity and reliability (94–97%), making them feasible to implement. The implementation of the STEAM–ESD-based BIOTEKS chatbot significantly improved students' scientific literacy with high N-gain values in both classes (0.99 and 0.77), as well as significant Mann Whitney U Test values between classes ($p = 0.199$). The most prominent improvement occurred in scientific representation and data interpretation abilities in the context of sustainable biotechnology. It can be concluded that the STEAM–ESD-based BIOTEKS chatbot is effective as an innovative learning medium to improve students' scientific literacy and serves as a pedagogical reinforcer in contextual and sustainability-oriented 21st-century biology learning.

Keywords: Artificial intelligence; biotechnology; chatbot; science literacy; STEM-ESD

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INTRODUCTION

The industrial revolution 4.0 has significantly transformed human activities through the integration of technology with the Internet of Things (IoT) and artificial intelligence (AI), which greatly supports new innovations (Selamat & Windasari, 2021; Pratiwi & Indana, 2022). The rapid surge of information inevitably impacts science education, with implications for the use of technology to meet future needs (Yuliati & Saputra, 2019; Zhang & Aslan, 2021). Easy access to information in the technological era must be accompanied by appropriate knowledge, attitudes, and skills (Sakti et al., 2021) to prevent misuse of information (Jamaluddin & Hadijah, 2020; Salsabila et al., 2024) and to enable students to solve problems related to the environment, health, economics, social issues, and technology, which are essential for teaching scientific literacy. However, Indonesian students' level of scientific literacy remains relatively low.

Based on PISA 2022 and the nature of the science literacy test (NoSLiT), scientific literacy in grade XII high school students is classified as quite low (Takda et al., 2023). This

indicates that students often have difficulty interpreting data, evaluating evidence, and applying scientific concepts in real contexts (Sari & Rosdiana, 2024). However, in 2023, the PISA ranking increased from 2018 (Kemendikbudristek, 2023a). The increase in the PISA ranking was influenced by several pandemic handling efforts by the Ministry of Education, Culture, Research, and Technology, one of which is online access and technology (Kemendikbudristek, 2023b). Literacy development can be supported through multimedia and digital technologies to prepare students who are scientifically literate and capable of critical, logical, and creative thinking (Pertiwi et al., 2018; Rahayu et al., 2022). In the context of science, biology and biotechnology, materials are included in one of the subjects that require visualization.

Scientific literacy encompasses more than just mastery of scientific concepts, but also the ability to understand, apply, and evaluate scientific information in various contexts (Jerrim & Moss, 2019). In biotechnology learning, low levels of scientific literacy are particularly evident in contexts where students are required to bridge abstract biological concepts with real-world issues, including food security, sustainability, energy, and environmental quality. This requires a contextual, interdisciplinary learning approach aligned with sustainability competencies. The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach supports problem-solving through interdisciplinary integration. STEAM focuses on delivering skill-building learning content (Saimon et al., 2025) and helping address real-world problems (Atiaturrahmaniah et al., 2022). Meanwhile, ESD (Education for Sustainable Development) is an educational framework that aims to develop students' critical awareness of sustainability issues, such as climate change, social justice, and sustainable consumption (UNESCO, 2023). ESD prepares students to make responsible and sustainable decisions. By implementing ESD, students can provide innovative solutions to sustainable environmental problems based on the results of their evaluation assessments (Seta et al., 2014). Through ESD, life will achieve better sustainability amidst natural limitations, by maintaining a balance of life from a social, economic, and of course, environmental perspectives (Kuhlman & Farrington, 2010). The combination of STEAM and ESD is a very suitable combination for use in biotechnology materials. However, the use of STEAM with AI technology requires the integration of sustainability values, cognitive competencies, and practical skills (Howard, 2023). Therefore, the use of artificial intelligence in the form of interactive chatbots can be an innovative solution in supporting STEAM-ESD-based learning.

Artificial intelligence, particularly chatbots, offers opportunities to enhance personalized learning and guide students through the inquiry process. AI chatbots aid in understanding biological concepts, significantly personalizing learning, and helping solve problems (Haidir et al., 2024; Puspitawati et al., 2024). Although chatbots have been used in science education, existing tools are generally limited to content delivery and have not been designed to integrate interdisciplinary STEAM–ESD competencies. The implementation of AI chatbot learning in education has not been specifically directed towards UNESCO's Education for Sustainable Development (ESDGs) educational goals. A frequently used chatbot, ChatGPT, often provides inaccurate, incorrect, and misleading output, sometimes providing answers that sound reasonable but are incorrect. Even the website link provided by ChatGPT is unavailable (Shuhaiber et al., 2025). In fact, chatbots are currently used in various sectors, including business, healthcare, education, etc. (Selamat & Windasari, 2021). Therefore, an AI chatbot with clear and guaranteed sources is needed. Furthermore, no previous research has developed an AI-based chatbot specifically for biotechnology learning to improve scientific literacy. This creates a clear gap. According to Purwianingsih et al., (2022) education is not limited to ESD alone but must include a touch of technology and learning that perfectly integrates technology (Rohman et al., 2024) Therefore, the STEAM approach serves as an alternative in accommodating biotechnology, ESD, and chatbots (Gunawan, 2019). The use of artificial intelligence in the form of interactive chatbots can be an innovative solution in supporting STEAM-ESD-based learning. Therefore, this

study aims to develop and evaluate a STEAM-ESD-based chatbot to improve students' scientific literacy in biotechnology learning. The integration of STEAM–ESD into AI chatbots is expected to provide a contextual, sustainable, and interactive learning experience that better supports students in understanding biotechnology concepts and applying them in real-life decision-making and can certainly improve students' scientific literacy skills.

Based on several studies conducted by Rahayu et al., (2021); Saimon et al., (2023); Akram et al., (2023); Muhanditsah et al., (2023); Yusuf et al., (2024); Nabillah & Ridlo, (2024) almost none of them discuss the use of STEAM-ESD oriented chatbots. In addition, the selection of biotechnology materials is still rarely combined with ESD.. In fact, biotechnology material is one of the crucial materials related to the environment. Biotechnology supports 8 of the 17 SDGs goals, namely: goal 2: zero hunger, goal 3: healthy and prosperous lives, goal 6: water and sanitation, goal 7: clean and affordable energy, goal 9: industry, innovation, and infrastructure, goal 12: responsible consumption and production, goal 14: marine ecosystems, and goal 15: terrestrial ecosystems (Alisjahbana & Murniningtyas, 2018). By implementing ESD, students can provide innovative solutions to sustainable environmental problems from the results of their evaluation assessments (Mochtar et al., 2014). Therefore, the novelty of this research is a learning tool that utilizes artificial intelligence technology "Chatbot" oriented STEAM-ESD, so that education contributes to the environment of current and future generations.

The chatbot will provide an overview, materials, and concepts related to global issues from SDGs 2 and 7 according to the focus of this research. Collaboration between STEAM and ESD, assisted by virtual reality, can significantly improve learning outcomes and motivation for sustainability (Hsiao & Su, 2021; Hariyono et al., 2023). Chatbots make the teaching and learning process more effective and can help develop various skills in learning (Okonkwo & Ade-Ibijola, 2021; Ramadani et al., 2025; Labadze et al., 2023) one of which is scientific literacy, a basic skill in science education (Muhanditsah, 2023).

Furthermore, another challenge faced in learning biology, particularly biotechnology, is the limited classroom time available, which is often insufficient to explore concepts, conduct practical work, and relate them to sustainability issues in depth. Teachers also struggle to provide learning media that accommodate students' diverse learning needs, particularly for topics requiring process visualization, data analysis, and simultaneous contextual understanding. This situation is exacerbated by the lack of digital learning resources integrated with the Merdeka curriculum and supporting transdisciplinary approaches such as STEAM–ESD. Meanwhile, advances in artificial intelligence technology present new opportunities for creating adaptive, interactive learning media that provide personalized feedback to students. AI-based chatbots have the potential to become learning assistants that not only present content but also guide scientific thinking, stimulate reflection, and facilitate sustainable problem-solving. Therefore, developing a chatbot specifically for biotechnology is relevant because it can bridge students' need for context-rich learning.

The initial stage of this research began with a needs analysis process, followed by bibliometric analysis using VOSviewer, with the Scopus database related to educational chatbots from 2019-2025. The number of studies focusing on chatbot-based learning in secondary science education remains limited.

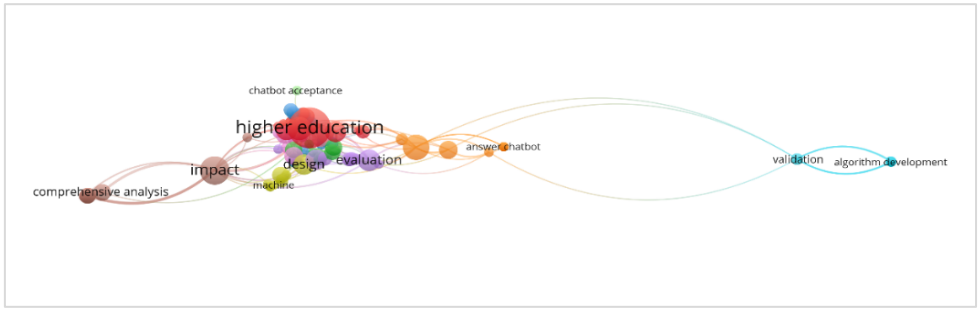

Figure 1. Bibliometric Analysis of Chatbot Research in Education

This research gap highlights the need to explore the potential of chatbots as innovative learning media to support students' scientific literacy. Therefore, this study aims to develop and evaluate the effectiveness of a STEAM–ESD-based chatbot learning device to improve students' scientific literacy.

METHODS

Research Design

This study uses a research and development (R&D) design with the ADDIE model (Branch, 2009). This study consists of 5 stages: analysis, design, development with validation and revision, implementation with small-scale testing for the first revision and large-scale trials, and finally evaluation. This study developed an AI chatbot based on STEAM-ESD. The developed chatbot has the advantage that all meta.AI data presented is clearly referenced and supports the learning process with a STEAM approach combined with sustainable development. This advantage has not been created before. This chatbot is named the "Bioteks" chatbot. Students will be given an initial literacy ability test to measure their initial abilities, then students will conduct practicums related to biotechnology material that supports sustainable development, all activities are carried out in the developed chatbot.AI. The chatbot learning tool was developed by analyzing the school curriculum, analyzing students, analyzing material concepts, and analyzing objectives and tasks in learning, developing tools, implementing, and conducting a final evaluation after learning. The treatment design is presented in Figure 2 and the research flow design is shown in Figure 3.

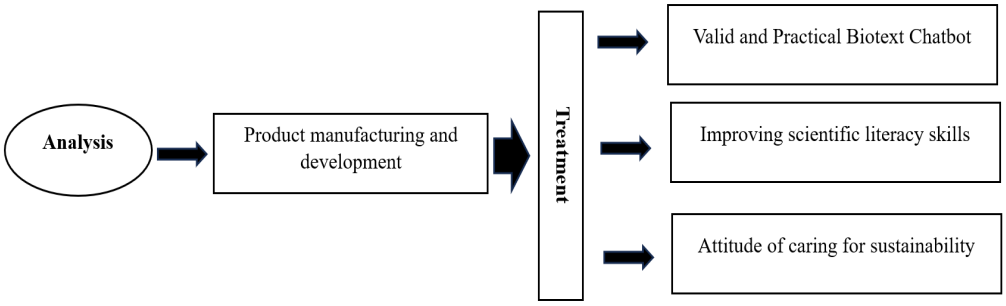

Figure 2. Research Treatment Design

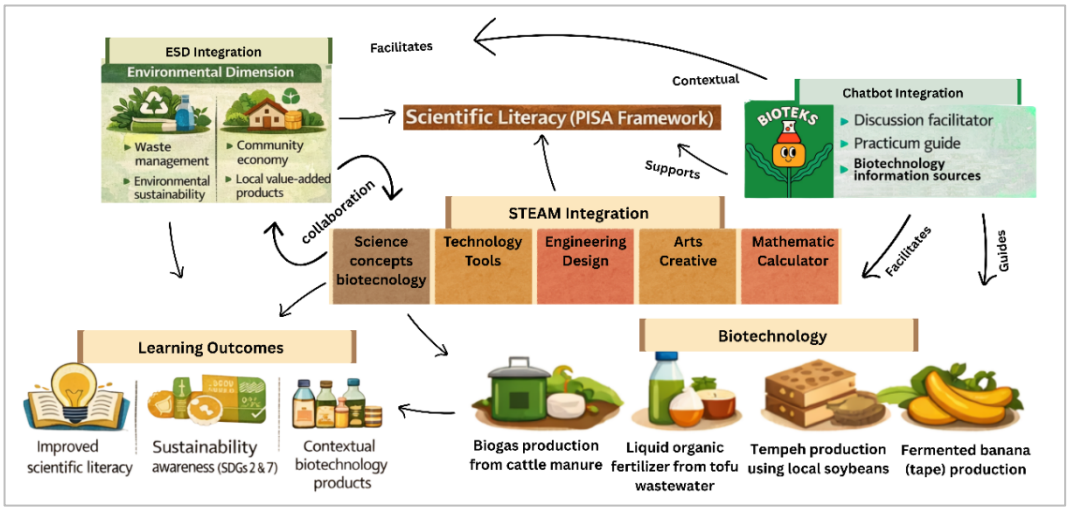

Figure 3. Learning Process Flowchart with STEAM-ESD Chatbot

The learning flow begins with an introduction to socio-scientific issues (SSI) related to environmental management and local economic sustainability. A STEAM-ESD-based chatbot serves as a digital learning facilitator, guiding students through project-based biotechnology inquiry, discussion, and practical activities. The integration of Education for Sustainable Development (ESD) emphasizes environmental responsibility and the value of a community-based economy. Through biotechnology projects, students engage in interdisciplinary STEAM learning. This learning design systematically supports the development of the five PISA scientific literacy indicators.

Participants

The participants of the research were 54 students, in 12th-grade, majoring in biology, which consists of 2 classes, namely class XII-A and XII-B, with 25 and 29 students in class. The students were divided into 8 groups. Each group included students with relatively higher academic performance who served as group coordinators. Each group conducted a practical experiment on creating biotechnology products that support continuing education.

Data Collection

The data collected included validation and effectiveness testing of the developed "Bioteks" chatbot learning device. The product developed in this study was limited to biotechnology material. The effectiveness of this product was tested on 12th-grade students of SMA Negeri 1 Pademawu, Pamekasan. The effectiveness test data collected was students' scientific literacy skills. During the data collection process, all instruments used were validated. The instruments used consisted of a "Bioteks" chatbot product validation sheet, a teaching module validation sheet, a student worksheet validation sheet, and a student science literacy test question validation sheet. Validation of all these tools involves learning from media experts, biologists, and education and learning experts.

Data analysis

Product validation data was processed from the validation sheet using a Likert scale. The product's validity level was calculated as a percentage by the validator, followed by its reliability. The "Bioteks" chatbot product was assessed on a scale of 81-100 (very valid), 61-80 (valid), 41-60 (fairly valid), 21-40 (less valid), and 0-20 (invalid). The reliability achievement level was categorized using four percentage ranges: reliable (76-100), fairly reliable (51-75), less reliable

(26-50), and unreliable (0-25). This was then reinforced with Rasch analysis for more accurate, objective, and unidimensional measurements.

The STEAM-ESD chatbot is said to be effective if the analysis uses the N-gain calculation in the medium to high category and if $t > tt_{able}$ or probability (sig.) < 0.05, in addition, normality and homogeneity tests are carried out to confirm the suitability of the parametric analysis, if the data is not normal and homogeneous, an inferential analysis test is carried out using the Mann–Whitney U test.

RESULTS & DISCUSSION

Result

Bibliometric analysis reveals that existing chatbot education research is largely concentrated in the context of higher education, with a strong emphasis on system development, algorithm validation, and user acceptance. Keywords such as "higher education," "development," and "AI chatbot" dominate the research landscape, indicating that most studies focus on technological aspects rather than pedagogical outcomes. Notably, clusters related to learning impact and comprehensive educational analytics appear relatively small, suggesting a research gap in examining chatbot integration within a structured pedagogical framework and its impact on students' scientific literacy. Therefore, this study addresses this identified gap by developing and implementing a STEAM-ESD-based educational chatbot to improve secondary school students' scientific literacy, going beyond technical validation to meaningful learning outcomes, particularly at the secondary education level. This is followed by an internal analysis.

The internal analysis begins with an analysis of the school curriculum, student analysis, material concept analysis, and analysis of learning objectives and tasks. The school curriculum used is an independent curriculum with a deep learning approach. Students are selected based on their interest in biology, as in high school, classes are divided according to student interests. Then, a conceptual analysis of the material to be used, namely biotechnology, is conducted. This is followed by the development of learning objectives and tasks for the learning process.

After the analysis process was carried out, the device development process continued, namely the creation of a STEAM-ESD-based “Bioteks” chatbot and supporting learning devices such as student worksheets, learning flows, and scientific literacy test questions. The relationships and indicators used in this study are presented in Table 1.

Table 1. Correlation of indicators in research

Science Literacy Indicators	STEAM-ESD	Student Assignments	Chatbot Features
Using various forms of representation and translating them.	Science: solving real environmental problems for sustainability.	solve the problems provided and represent them.	Provide reading resources that can be accessed directly.
Evaluating an appropriate experimental design to answer a research question.	Technology: access to knowledge without producing paper waste.	designing solutions to biotechnology problems and their impact on sustainability.	Provides an overview and how to design work to overcome problems.
Interpret the data presented, draw conclusions based on the data and evaluate their relative merits.	Engineering: becoming an agent of change capable of designing	design-thinking through the creation of biotechnology products.	Directing students to design

Science Literacy Indicators	STEAM-ESD	Student Assignments	Chatbot Features
	sustainable solutions.		sustainable research.
Constructing arguments to support sound scientific conclusions from a set of data.	Art: communicating sustainability values and fostering creativity.	Make a poster about how to solve environmental problems with biotechnology.	Directing and providing a place for collecting posters and activity documentation.
Criticizes standard weaknesses in science-related arguments and conclusions from limited data.	Mathematic: data-driven decision making and resource efficiency, which is economical, effective and sustainable.	Calculate, analyze, and evaluate.	Provide a place to collect work that is accessible to everyone.

All learning devices are very valid and very reliable with percentages as presented in table 2.

Table 2. Validation and Reliability of Teaching Tools

Teaching Tools	Percentage (%)
Bioteks Chatbot	94
Teaching Module	97
Student Worksheet	96
Science Literacy Test Questions	96

The results of the learning device validity analysis, with a score of 94–99%, strengthen the credibility of the research instrument, in accordance with the recommendations for educational instrument validation by Mohamad et al. (2015). With validity and reliability, the learning device is an indicator of suitability and appropriateness for use in biology lessons with a focus on biotechnology material to support sustainability education and improve the scientific literacy skills of grade XII high school students. The validity analysis was also analyzed using Rasch analysis, obtaining the data in Table 3.

Table 3. Rasch Analysis

MSQN	ZSTD	CORR.	Category
1.45	2.82	0.17	Valid
1.20	0.93	0.30	Valid
1.10	0.42	0.32	Valid
0.85	-0.17	0.23	Valid
0.96	-0.10	0.38	Valid
1.00	0.06	0.39	Valid
0.98	-0.05	0.45	Valid
0.75	-1.03	0.46	Valid
0.72	-1.47	0.52	Valid
0.86	-0.29	0.41	Valid
0.79	-0.83	0.48	Valid

Rasch analysis showed that all items of the STEAM-ESD-based scientific literacy instrument were in the model fit category, the instrument was declared empirically valid. The results showed that all items met the model fit criteria, indicated by the MNSQ Infit and Outfit

values ranging from 0.72–1.45, and the PTMEA values were all positive. These findings confirm that the instrument has good construct validity.

The effectiveness analysis shows that the integration of the STEAM-ESD-based BIOTEKS chatbot significantly improves students' scientific literacy in biotechnology learning. This improvement is evident from the high N-gain scores obtained by both classes, with Class XII-1 achieving an average of 0.99 and Class XII-2 achieving 0.77. The difference in pretest and posttest scores indicates that scientific literacy skills, which are generally low, improved after the treatment and posttest.

Table 4. N-Gain Score Improvement

Class	Pretest (Mean)	Posttest (Mean)	N-gain	Category
XII-1	3.72	8.44	0.99	High
XII-2	3.62	7.88	0.77	High

These findings indicate that the chatbot-supported learning process was effective across all classes. The results of the Mann–Whitney test can be seen in Table 5.

Table 5. Mann-Whitney U test

Test	U	Z	p
Mann–Whitney U	266	–1.285	0.199

The results of the analysis using the Mann–Whitney U test showed that there was no significant difference between the scientific literacy scores of students in grades XII-1 and XII-2 ($U = 266$; $Z = -1.285$; $p = 0.199 > 0.05$). These results indicate that the implementation of the developed learning tools had a relatively similar effect on both classes. These findings indicate that the STEAM–ESD-based learning tools used were effective and consistent in facilitating the improvement of students' scientific literacy, so they can be applied to different classes with similar results.

These findings align with research (Yusup & Kurniawan, 2024) showing that chatbots provide positive learning outcomes for groups of students, but are still influenced by variations in ability, intrinsic motivation, and other contextual factors. This success is also supported by analysis in research by Xu and Ouyang (2022) which states AI tutoring systems can have a uniform effect on STEM learning. From a STEAM perspective, the BIOTEKS chatbot facilitates the integration of science, technology, engineering, visual arts, and mathematics concepts in the context of biotechnology. This type of integration model has been shown to increase conceptual connectivity and applicability to real-world problems (Quigley et al., 2019). From the ESD side, the chatbot provides context for sustainability issues such as bioenergy, food security, and biotechnology ethics, which are proven to increase awareness of the sustainability of SDGs 2 and 7. In the learning process, students are directed to solve real problems by thinking from the ESD side, namely making biogas from cow dung from students' farms, making organic liquid fertilizer from waste tofu which is the first source of seawater pollution in Madura, making tempeh from local soybeans, and making banana tape from bananas planted in students' rice fields, where almost all of the students' parents work as farmers. So the problems solved by students are socio-scientific issues.

An analysis of each indicator was also conducted to determine which indicator provided the most optimal improvement. The analysis of each indicator is shown in Figure 4 below.

Figure 4. Analysis of each indicator

Discussion

The very high N-gain value in class XII-1 (0.99) and high in class XII-2 (0.77) indicates that the chatbot not only functions as a medium for conveying information, but also as a learning medium capable of facilitating the construction of deeper knowledge, as also reported by Huang et al. (2025) and Pan et al. (2023). The greatest increase occurred in the indicator of the ability to interpret scientific representations. This is in accordance with the findings Rahmayani et al. (2024) that multiple representations improve concept integration and deeper understanding. The BIOTEKS chatbot provides multimedia learning, including videos, quizzes, and visualizations of biotechnology processes, which help build a consistent conceptual scheme, as also found in Zainal (2024) research regarding the role of visualization in biology learning. This is in line with multimedia learning theory (Mayer, 2021), and the findings of Fitriasih et al. (2025) which show that multimedia can reduce cognitive load and help understand abstract biotechnology processes. However, improvements in representation indicators do not automatically translate into similar improvements in higher-order thinking skills, such as designing experiments, evaluating experiments, constructing arguments, and justifying scientific decisions. Numerous studies confirm that higher-order scientific reasoning requires time, dialogue, and empirical experience that cannot be replaced by visual exposure alone (Erduran & Jiménez-Aleixandre, 2016; Muis et al., 2021). Emphasized that scientific reasoning understanding develops through laboratory work, collaboration, and in-depth reflection. This corresponds to findings (Ramli et al., 2025) that chatbots tend to strengthen understanding but do not fully stimulate the cognitive conflict required for higher-order scientific argumentation. However, the analysis showed improvements across treatment classes. Overall, the research results indicate that the implementation of the STEAM-ESD-based BIOTEKS chatbot in biotechnology learning significantly improves students' scientific literacy. This finding is in line with various studies showing that AI-based chatbots are able to improve students' mastery of science concepts, metacognition, and self-regulation through adaptive interactions (Waziana et al., 2024; Yin et al., 2024).

The integration of AI and ESD also aligns with the global trend of utilizing technology for sustainability learning (Nurwidianti, 2024). Dialogue-based interactions in chatbots provide metacognitive support through adaptive questioning, feedback looping, and personalized learning rhythms. Research (Cao et al., 2023) shows that chatbots can act as social agents that increase motivation and psychological support. Research by Husein et al. (2024) also shows that chatbots in the science field significantly improve engagement and understanding.

The limitations of chatbots in improving scientific argumentation are still evident in the results of this research analysis. Various studies also show that argumentation requires dialogue between students, negotiation of meaning, and collective, evidence-based reasoning. Admoko

et al. (2025) also emphasized that argumentation does not develop optimally in environments that provide too many direct answers. This is one of the fundamental limitations of chatbots as a substitute for human interaction. Chatbots have proven effective as pedagogical amplifiers (Jamil et al., 2021), not as a substitute for active pedagogy. Therefore, the use of chatbots should be combined with inquiry-based learning approaches (Rismayanti & Purmadi, 2025), socio-scientific issues (Rauch & Radmann, 2020), or project-based learning that provides more space for argumentation skills. This integration is crucial for improving indicators 2–5, which have seen more moderate increases. In terms of practical implications, chatbots help reduce student ability gaps (Wang et al., 2024), support personalization (Ch et al., 2025), and strengthen prior understanding before laboratory-based learning. This is relevant to the Merdeka curriculum, which emphasizes independence and project-based learning.

Overall, these findings suggest that the BIOTEKS chatbot has strong potential for improving scientific literacy, particularly the representation and understanding of biotechnology concepts. However, to improve scientific argumentation skills and evidence-based decision-making, integration with collaborative pedagogy and laboratory experiences is necessary. This confirms the chatbot's position as a pedagogical enhancer in STEAM–ESD in 21st-century learning. Furthermore, student engagement in project-based activities through the chatbot also demonstrates that digital media can enhance collaborative learning processes. These interactions not only help students understand biotechnology concepts but also foster a sense of responsibility, independence, and ecological awareness, which are essential foundations for sustainable education.

CONCLUSION

This study shows that the STEAM-ESD-based BIOTEKS chatbot is effective in improving students' scientific literacy in biotechnology learning. High N-gain scores indicate significant improvements in both classes, while the Mann–Whitney U test showed no significant differences between groups, indicating that the chatbot provides consistent learning outcomes across classes. These findings highlight the potential of AI-based chatbots as innovative learning tools to support interdisciplinary and sustainability-oriented science education. Suggestions for future research should explore the long-term impact of chatbot-assisted learning on higher-order scientific reasoning and argumentation skills, as well as integrating the use of chatbots with collaborative and inquiry-based learning to further optimize the role of artificial intelligence in science education.

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REFERENCES

Admoko, S., Hariyono, E., Madlazim, & Dwikoranto. (2025). Trens of science education research on argumentation skills and the contribution of Indonesia. *Journal of Lifestyle & SDG'S Review*, *5*(1), 1–20. https://doi.org/https://doi.org/10.47172/2965-

730X.SDGsReview.v5.n02.pe02311

Akram, M. H., Nadrah, N., & Tahir, R. (2023). Peningkatan hasil belajar IPA melalui media interaktif digital berbasis chatbot pada siswa kelas IV 2 UPT SD Negeri 8 KBinamu, Kecamatan Binamu, Kabupaten Jeneponto. *Sinar Dunia: Jurnal Riset Sosial Humaniora Dan Ilmu Pendidikan*, *2*(2), 01–25. https://doi.org/10.58192/sidu.v2i2.770

Atiaturrahmaniah, A., Bagus, I., Aryana, P., & Suastra, I. W. (2022). Peran Model Science, Technology, Engineering, Arts, and Math (STEAM) dalam meningkatkan berpikir kritis dan literasi sains siswa sekolah dasar. *JPGI (Jurnal Penelitian Guru Indonesia)*, *7*(2), 368–375.

Branch, R. M. (2009). *Instructional Design: The ADDIE Approach* (1st ed.). Springer US. https://doi.org/10.1007/978-0-387-09506-6

Cao, C. C., Ding, Z., Lin, J., & Hopfgartner, F. (2023). AI chatbots as multi-role pedagogical agents : transforming engagement in cs education. *Cornell University*, *4*, 1–8. https://doi.org/https://doi.org/10.48550/arXiv.2308.03992

Ch, W. V., Fernandez, D. B., & Navarro, A. M. (2025). Adaptive intelligent tutoring systems for STEM education : analysis of the learning impact and effectiveness of personalized feedback. *Smart Learning Environments*, *12*(41), 1–31. https://doi.org/https://doi.org/10.1186/s40561-025-00389-y Smart

Erduran, S., & Jiménez-Aleixandre, M. P. (2016). Argumentation in science education. *Revista Brasileira de Linguística Aplicada*, *5*(1), 1689–1699.

Fitriasih, F., Handayani, T., & Isfaeni, H. (2025). Smart biotech learning media: A STEAM-IoT based to improve students' problem-solving abilities and collaboration skills. *JPBI (Jurnal Pendidikan Biologi Indonesia)*, *11*(2), 450–459. https://doi.org/10.22219/jpbi.v11i2.39941

Gunawan, P. (2019). Model pembelajaran STEAM (Scient, Technology, Engineering, Art, Mathematics) dengan pendekatan saintifik. *Model Pembelajaran STEAM*, 1–64.

Haidir, H., Muhamad, T., Roviati, R., Evi, E., & Deka, D. (2024). Penerapan Chat GPT dalam pembelajaran biologi. *Jurnal Sosial Teknologi*, *4*(3), 182–189. https://doi.org/10.59188/jurnalsostech.v4i3.1064

Hariyono, E., Suprapto, N., Zakhiyah, I., & Ismail, M. H. (2023). Development of dye-sensitized solar cells steam learning prototype for supporting educational for sustainable development. *EUREKA, Physics and Engineering*, *2023*(5), 56–66. https://doi.org/10.21303/2461-4262.2023.002928

Howard, P. (2023). Who will teach the teachers?: reorienting teacher education for the values of sustainability. *Teaching Sustainability / Teaching Sustainably*, 149–157. https://doi.org/10.4324/9781003447429-15

Hsiao, P. W., & Su, C. H. (2021). A study on the impact of steam education for sustainable development courses and its effects on student motivation and learning. *Sustainability (Switzerland)*, *13*(7), 1–24. https://doi.org/10.3390/su13073772

Huang, X., Xu, W., Liu, R., & Yu, Z. (2025). Effects of intelligent tutoring systems on educational outcomes: evidence from a comprehensive analysis. *International Journal of Distance Education Technologies*, *23*(1), 1–25. https://doi.org/10.4018/IJDET.368420

Husein, D. F. Al, Haristiani, N., Wahyu, W., & Rasim, R. (2024). Chatbot artificial intelligence as educational tools in science and engineering education : a literature review and bibliometric mapping analysis with its advantages and disadvantages. *ASEAN Journal of Science and Engineering*, *4*(1), 93–118. https://doi.org/https://doi.org/10.17509/ajse.v4i1.67429

Jamaluddin, & Hadijah, S. (2020). Pengaruh penyalahgunaan teknologi informasi dan integritas mahasiswa terhadap perilaku kecurangan akademik mahasiswa akuntansi sebagai calon

akuntan. *Jurnal of Economic, Public, and Accounting (JEPA)*, *2*(2), 158–168.
Jamil, M. W., Andriani, L., Nurkhalishah, S., & Nuraeni, E. (2021). The potency of using chatbot in online biology learning. *SN Biosfer*, *3*(3), 255–262.
Jerrim, J., & Moss, G. (2019). The link between fiction and teenagers' reading skills: International evidence from the OECD PISA study. *British Educational Research Journal*, *45*(1), 181–200. https://doi.org/10.1002/berj.3498
Kemendikbudristek. (2023a). Peringkat Indonesia pada PISA 2022 Naik 5-6 Posisi Dibanding 2018. *GTK Kemendikbud*, 1. https://gtk.kemdikbud.go.id/read-news/peringkat-indonesia-pada-pisa-2022-naik-56-posisi-dibanding-2018
Kemendikbudristek. (2023b). PISA 2022 dan pemulihan pembelajaran di indonesia. *Laporan Pisa Kemendikbudristek*, 1–25.
Kuhlman, T., & Farrington, J. (2010). What is sustainability? *Sustainability*, *2*(11), 3436–3448. https://doi.org/10.3390/su2113436
Labadze, L., Grigolia, M., & Machaidze, L. (2023). Role of AI chatbots in education: systematic literature review. *International Journal of Educational Technology in Higher Education*, *20*(1), 1–17. https://doi.org/10.1186/s41239-023-00426-1
Mayer, R. E. (2021). Multimedia learning (3rd ed.). Cambridge University Press
Mohamad, M. M., Sulaiman, N. L., Sern, L. C., & Salleh, K. M. (2015). Measuring the validity and reliability of research instruments. *Procedia - Social and Behavioral Sciences*, *204*(November 2014), 164–171. https://doi.org/10.1016/j.sbspro.2015.08.129
Muhanditsah, S. (2023). Pengaruh pendekatan stem berbantuan chatbot untuk meningkatkan kemampuan literasi sains siswa sekolah dasar. *repository.upi.edu*. Universitas Pendidikan Indonesia.
Muhanditsah, S., Putri, H. E., & Rahayu, P. (2023). Pengaruh pendekatan stem berbantuan chatbot untuk meningkatkan literasi siswa sekolah dasar. *Prosiding Simposium Nasional Multidisiplin (SinaMu)*, *4*(2021), 24. https://doi.org/10.31000/sinamu.v4i1.7665
Muis, K. R., Chevrier, M., Denton, C. A., & Losenno, K. M. (2021). Epistemic emotions and epistemic cognition predict critical thinking about socio-scientific issues. *Frontiers in Education*, *6*(April), 1–18. https://doi.org/10.3389/feduc.2021.669908
Nabillah, Z., & Ridlo, Z. R. (2024). Pengembangan media pembelajaran chatbot berbasis web dalam pembelajaran ipa smp untuk meningkatkan keterampilan berpikir kreatif siswa. *Journal of Science Education*, *8*(3), 427–433.
National Research Council. (2012). *A framework for K–12 science education.* National Academies Press. https://doi.org/10.17226/13165
Nurwidianti, D. (2024). Integrasi Education for Sustainable Development (ESD) Berbasis Teknologi Dasar. *Seminar Nasional Pendidikan Dasar*, *8*(8), 138–154.
Okonkwo, C. W., & Ade-Ibijola, A. (2021). Chatbots applications in education: A systematic review. *Computers and Education: Artificial Intelligence*, *2*, 100033. https://doi.org/10.1016/j.caeai.2021.100033
Pan, C. S., Leung, S. K. Y., & Wan, S. W. yan. (2023). Unlocking emotional aspects of kindergarten teachers' professional identity through photovoice. *Education Sciences*, *13*(4). https://doi.org/10.3390/educsci13040342
Pertiwi, U. D., Atanti, R. D., & Ismawati, R. (2018). Pentingnya literasi sains pada pembelajaran ipa smp abad 21. *Indonesian Journal of Natural Science Education (IJNSE)*, *1*(1), 24–29. https://doi.org/10.31002/nse.v1i1.173
Pratiwi, M. K., & Indana, S. (2022). Pengembangan E-modul berbasis qr-code untuk melatihkankemampuan literasi digital siswa pada materi perubahan lingkungan. *Berkala Ilmiah Pendidikan Biologi (BioEdu)*, *11*(2), 457–468. https://doi.org/10.26740/bioedu.v11n2.p457-468

Purwianingsih, W., Novidsa, I., & Riandi, R. (2022). Program for integrating education for sustainable development (esd) into prospective biology teachers' technological pedagogical content knowledge (tpack). *Jurnal Pendidikan IPA Indonesia*, *11*(2), 219–228. https://doi.org/10.15294/jpii.v11i2.34772

Puspitawati, R. P., Afnan, M. Z., Abrizal, H. P., Anjani, G. A. D. K., & Adisatria, B. (2024). Artificial intelligence dalam artikel pendidikan biologi pada rentang tahun 2003-2024. *Prosiding Seminar Nasional Biologi*, *IP2B VIII*, 44–60.

Quigley, C., Herro, D., & Davis, K. (2019). Moving toward transdisciplinary instruction: A STEAM framework. *Science Education*, 104(5), 1050–1071. https://doi.org/ 10.1007/978-3-030-04003-1_8

Rahayu, I. K., Sanjaya, Y., & Solihat, R. (2021). Integration of SDGs in environmental education subjects of adiwiyata vocational high school. *Journal of Physics: Conference Series*, *1806*(1). https://doi.org/10.1088/1742-6596/1806/1/012167

Rahayu, S., Isnaeni, W., & Masturi, M. (2022). Critical thinking skills and digital literacy of high school students in science learning using e-learning with stem vision. *Journal of Innovative Science Education*, *11*(3), 347–361. https://doi.org/10.15294/jise.v11i1.57281

Rahmayani, F., Kuswanto, H., & Rahmat, A. D. (2024). Development of E-book integrated augmented reality based on stem approaches to improve critical thinking and multiple representation skills in learning physics. *International Journal of Information and Education Technology*, *14*(4), 632–641. https://doi.org/10.18178/ijiet.2024.14.4.2087

Ramadani, S., Fadilah, N. S., Ferdina, S., & Winda, M. (2025). Efektivitas penggunaan chatbot ai sebagai media pembelajaran interaktif terhadap keterampilan logika pemrograman siswa smk kelas 12 tkj. *EDUTEACH: Jurnal Pendidikan dan Teknologi Pembelajaran,06*(01). 20-28.

Ramli, N. A., Nur, S., & Mahmud, D. (2025). Integration of artificial intelligence to support inquiry-based science teaching and learning : a systematic literature review. *International Journal of Academic*, *14*(2), 893–911. https://doi.org/10.6007/IJARPED/v14-i2/25380

Rauch, F., & Radmann, D. (2020). How socio-scientific inquiry based learning (ssibl) promotes inquiry in climate issues – an example for enacting socio-scientific issues in science education. *Action Research and Innovation in Science Education*, *3*(2), 43–45. https://doi.org/https://doi.org/10.12973/arise/164872

Rismayanti, E., & Purmadi, A. (2025). Strategi implementasi inquiry learning model untuk meningkatkan critical thinking skills siswa berbantuan ChatGPT. *Journal Pendidikan Indonesia: Teori, Penekitian Dan Inovasi*, *4*(5), 28–34. https://doi.org/10.59818/jpi.v5i4.1740

Rohman, F., Novianti, V., & Rizqi Nur Rachmawati. (2024). *Machine Translated Biosfer : Jurnal Pendidikan Biologi by Google*. 406–420.

Saimon, M., Lavicza, Z., Houghton, T., Mtenzi, F., & Carranza, P. (2025). A model for utilising crises-related issues to facilitate transdisciplinary outdoor STEAM education for sustainability in integrated mathematics, language arts and technology classrooms. *Discover Education*, *4*(1). https://doi.org/10.1007/s44217-025-00405-w

Saimon, M., Lavicza, Z., Houghton, T., & Rahmadi, I. (2023). A model for integrating microgames in teaching primary education for sustainable development. *Journal of Research in Innovative Teaching and Learning*, 448–458. https://doi.org/10.1108/JRIT-12-2022-0085

Sakti, I., Nirwana, N., & Swistoro, E. (2021). Penerapan model project based learning untuk meningkatkan literasi sains mahasiswa pendidikan IPA *Jurnal Kumparan Fisika*, *4*(1), 35–42. https://doi.org/10.33369/jkf.4.1.35-42

Salsabila, A., Hidayati, S. N., & Aulia, E. V. (2024). Analisis kemampuan literasi informasi siswa smp dalam menghadapi pembelajaran di era society 5 . 0. *Nusantara: Jurnal Pendidikan Indonesia*, *4*(2), 570–580.

Sari, I. J., & Rosdiana, R. (2024). Analisis literasi sains siswa sma pada konsep pencemaran lingkungan. *Jurnal Penelitian Sains dan Pendidikan (JPSP)*, *4*(1), 33–42. https://doi.org/10.23971/jpsp.v4i1.7862

Selamat, M. A., & Windasari, N. A. (2021). Chatbot for SMEs: Integrating customer and business owner perspectives. *Technology in Society*, *66*(January), 101685. https://doi.org/10.1016/j.techsoc.2021.101685

Seta; Ananto Kusuma; Mochtah, N. E. (2014). Pendidikan untuk pembangunan berkelanjutan (education for sustainable development) di indonesia. In *Kementrian Pendidikan dan Kebudayaan* (Issue 9).

Shuhaiber, A., Kuhail, M. A., & Salman, S. (2025). ChatGPT in higher education - A Student's perspective. *Computers in Human Behavior Reports*, *17*(November 2024), 100565. https://doi.org/10.1016/j.chbr.2024.100565

Takda, A., Arifin, K., & Tahang, L. (2023). Profil kemampuan literasi sains peserta didik sma berdasarkan nature of science literacy test (NoSLiT). *Jurnal Penelitian Pendidikan Fisika*, *8*(1), 19–27. https://doi.org/10.36709/jipfi.v8i1.7

UNESCO. (2023). *Transforming education together : ESD-NET Global Meeting* (Issue December).

Wang, S., Wang, F., Zhu, Z., Wang, J., Tran, T., & Du, Z. (2024). Artificial intelligence in education : A systematic literature review. *Expert Systems with Applications*, *252*(PA), 124167. https://doi.org/10.1016/j.eswa.2024.124167

Waziana, W., Andewi, W., Hastomo, T., & Hasbi, M. (2024). Students' perceptions about the impact of ai chatbots on their vocabulary and grammar in efl writing. In *Register Journal, 17(2)*. 352–382. https://doi.org/10.18326/register.v17i2.352-382

Xu, W., & Ouyang, F. (2022). The application of AI technologies in STEM education: a systematic review from 2011 to 2021. *International Journal of STEM Education*, *9*(1). https://doi.org/10.1186/s40594-022-00377-5

Yin, J., Zhu, Y., Goh, T. T., Wu, W., & Hu, Y. (2024). using educational chatbots with metacognitive feedback to improve science learning. *Applied Sciences (Switzerland)*, *14*(20). https://doi.org/10.3390/app14209345

Yuliati, Y., & Saputra, D. S. (2019). Pembelajaran sains di era revolusi industri 4.0. *Jurnal Cakrawala Pendas*, *5*(2), 167–171.

Yusuf, H. B., Setiawan, A. (2024). Pengembangan Tutor virtual chatbot untuk mahasiswa. *JIKA (Jurnal Informatika)*, *8*(4), 364–373.

Yusup, M., & Kurniawan, R. (2024). Memahami dampak teknologi chatbot dalam pembelajaran : analisis pemanfaatan di sma negeri 5 binjai. *Seminar Nasional Sosial Humaniora & Teknologi 2024*, *1*(1), 518–524.

Zainal, A. (2024). Efektivitas media visual dalam meningkatkan pemahaman konsep biologi di sekolah menengah ata. *Jurnal Ilmiah IPA dan Matematika*, *2*(1), 12–16. https://jurnalcendekia.id/index.php/jiim/

Zhang, K., & Aslan, A. B. (2021). AI technologies for education: Recent research & future directions. *Computers and Education: Artificial Intelligence*, *2*, 100025. https://doi.org/10.1016/j.caeai.2021.100025