BIO EDUCATIO
(*The Journal of Science and Biology Education*)
http: https://jurnal.unma.ac.id/index.php/BE
p-ISSN : 2541-2280
e-ISSN : 2541-4097
DOI: http://doi.org/10.31949/be.v10i2.15491

Enhancing 21st-Century Skills through Sustainability-Oriented Biology Learning: A Systematic Literature Review

Titis Dewi Vira[1]*, Eny Hartadiyati Wasikin[2], Fibria Kaswinarni[3], Muhamad Syaipul Hayat[4]
[1] Biology Education Study Program, Universitas PGRI Semarang, Indonesia
[2] Master's Program in Science Education, Universitas PGRI Semarang, Indonesia
[3] Biology Education Study Program, Universitas PGRI Semarang, Indonesia
[4] Biology Education Study Program, Universitas PGRI Semarang, Indonesia
Corresponding author: titisvira788@gmail.com

Article Info
Article History
Received: 20-09-2025
Revised: 18-10-2025
Accepted: 20-10-2025

Keywords:

Education for Sustainable Development;
Sustainability-Oriented Learning;
Biology Education;
21st-Century Skills;
Critical Thinking;
Creative Thinking

ABSTRACT
This study aims to systematically analyze the contribution of sustainability-oriented biology learning to the development of 21st-century skills, particularly critical thinking, creative thinking, and collaboration. A systematic literature review (SLR) design was employed following PRISMA procedures to ensure a transparent and structured selection process. A total of 24 articles published between 2019 and 2024 were selected from Scopus, ERIC, and Google Scholar based on predefined inclusion criteria. Data were extracted using a structured matrix and analyzed through thematic synthesis to identify patterns, instructional approaches, and skill outcomes. The findings indicate that critical thinking is the most dominant competency (75%), followed by creativity (62.5%) and collaboration (54.2%). Education for Sustainable Development (ESD) and socioscientific issues (SSI) approaches show the strongest contribution to critical thinking, while project-based and STEM/STEAM approaches are more closely associated with creativity and collaboration. Technology-enhanced learning supports engagement and interaction but demonstrates less consistent impact on higher-order thinking. Overall, the results suggest that sustainability-oriented biology learning provides a strong pedagogical foundation for developing 21st-century skills. However, its effectiveness depends on the alignment between instructional approaches, learning contexts, and targeted competencies. This study contributes to strengthening the theoretical and practical understanding of sustainability education in biology learning.

INTRODUCTION

The escalating environmental crisis, reflected in deforestation, land degradation, and excessive resource exploitation, has become a pressing global concern that directly affects ecological balance and human sustainability. In Indonesia, rapid development across economic, infrastructural, and educational sectors has contributed not only to national progress but also to environmental degradation, particularly in terms of biodiversity loss and ecosystem instability. This condition calls for a shift in educational orientation, where learning is no longer limited to knowledge transmission but also emphasizes the development of environmental awareness and

responsibility. Education is expected to function as a transformative space that prepares learners to respond to real-world sustainability challenges. In this context, science education holds a strategic role because it connects conceptual understanding with environmental phenomena and societal issues. As noted by Hogan and O'Flaherty (2021), sustainability-oriented science education can foster learners' capacity to engage with complex environmental problems, while González-Gómez and Jeong (2022) emphasize that integrating sustainability into science teaching enhances the relevance of learning in addressing global challenges

Education for Sustainable Development (ESD) provides a comprehensive framework for integrating environmental, social, and economic dimensions into educational practices. Rather than focusing solely on theoretical content, ESD promotes learning processes that are interdisciplinary, contextual, and oriented toward real-life problem solving. Through this approach, students are encouraged to develop critical awareness, ethical responsibility, and active participation in sustainability issues. In the context of biology education, ESD enables students to understand the interconnections between ecological systems and human activities. Empirical studies show that integrating ESD into biology learning enhances students' ability to think systemically and solve problems based on environmental contexts. Saragih et al. (2021) found that ESD implementation supports the development of problem-solving skills, while Ekamilasari and Pursitasari (2021) reported improvements in students' critical thinking and sustainability awareness. Similarly, Dara (2024) highlights that ESD-based biology learning strengthens students' engagement with climate-related issues, making learning more meaningful and applicable

At the same time, the demands of the 21st century require learners to master essential competencies, particularly critical thinking, creative thinking, and collaboration. These competencies are increasingly regarded as fundamental for navigating complex and uncertain global contexts. Biology education provides a relevant platform for developing such competencies because it deals with real-world issues, including environmental sustainability and ecological interactions. Through inquiry and problem-based learning, students are encouraged to analyze data, evaluate evidence, and generate innovative solutions. Research indicates that the transformation of science learning approaches contributes significantly to the development of higher-order thinking skills. Kurniawan et al. (2024) argue that modern science learning, supported by innovative technologies, strengthens students' critical thinking abilities, while Fuadiyah et al. (2022) demonstrate that biology learning models can effectively improve students' analytical skills when designed to promote active engagement. These findings suggest that biology education plays a crucial role in aligning learning processes with the demands of 21st-century competencies

Previous studies have consistently shown that the integration of sustainability principles into biology learning—through approaches such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), and inquiry-based models—can enhance students' higher-order thinking skills. PBL, for example, encourages students to engage with authentic environmental problems, which in turn strengthens their critical thinking and reasoning abilities. Usman et al. (2024) report that PBL in biology learning effectively improves students' capacity to analyze and solve complex problems. Meanwhile, project-based approaches provide opportunities for students to develop creativity through the design of solutions to sustainability-related challenges. Francisco et al. (2024) found that collaborative project-based learning fosters both communication and teamwork skills, while Setiyaningsih et al. (2024) demonstrate that inquiry-based learning integrated with ESD

enhances critical thinking and sustainability awareness. In addition, Fatimah et al. (2023) highlight that ESD-based learning models contribute to improved critical thinking through structured scientific activities. Despite these findings, existing studies remain fragmented and often focus on specific skills or instructional models, leaving a gap in comprehensive synthesis

Furthermore, many literature-based studies in this field have not applied rigorous and transparent analytical procedures, which limits the strength of their conclusions and theoretical contributions. The absence of systematic synthesis makes it difficult to identify patterns, compare findings, and draw comprehensive insights regarding the effectiveness of sustainability-oriented biology learning. As highlighted by Fathurohman et al. (2023), systematic literature reviews are essential for integrating diverse findings and strengthening the evidence base in education research. Without such an approach, the relationship between sustainability-based learning and the development of multiple dimensions of 21st-century skills remains insufficiently explored. Therefore, there is a need for a more structured and analytical review that not only compiles existing studies but also critically examines their contributions and limitations.

Based on these considerations, this study aims to systematically analyze and synthesize existing research on sustainability-oriented biology learning, with a particular focus on its contribution to the development of 21st-century skills, including critical thinking, creative thinking, and collaboration. By providing a comprehensive and analytically grounded review, this study is expected to contribute to the strengthening of theoretical frameworks and offer practical insights for the design of more effective and relevant biology learning in the context of sustainable development.

METHOD

Research Design

This study employed a systematic literature review (SLR) design to examine the contribution of sustainability-oriented biology learning to the development of 21st-century skills, particularly critical thinking, creative thinking, and collaborative skills. A systematic review was selected to ensure a structured, transparent, and reproducible process in identifying, evaluating, and synthesizing relevant studies. This approach enables the integration of findings across multiple empirical studies and provides a comprehensive understanding of patterns, trends, and research gaps within the field. The review process was guided by established systematic review principles to enhance the rigor and reliability of the findings.

Search Strategy

The literature search was conducted using several reputable academic databases, including Scopus, Google Scholar, and ERIC, to ensure comprehensive coverage of relevant studies. The search process applied Boolean operators and keyword combinations derived from the main constructs of the study, including *"education for sustainable development," "sustainability-oriented learning," "biology education,"* and *"21st-century skills."* Additional keywords such as *"critical thinking," "creative thinking,"* and *"collaboration"* were used to refine the search results. The search was limited to articles published between 2019 and 2024 to capture recent developments in sustainability-oriented education and 21st-century competencies.

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the selected studies, specific inclusion and exclusion criteria were applied. The inclusion criteria consisted of: (1) empirical studies or review articles focusing on sustainability-oriented learning or ESD in biology or science education; (2) studies examining at least one component of 21st-century skills; (3) articles published in peer-reviewed journals or reputable conference proceedings; and (4) publications written in English or Indonesian. Meanwhile, exclusion criteria included: (1) studies not related to education or sustainability learning; (2) articles lacking clear methodological descriptions; and (3) duplicate publications across databases.

Study Selection Process

The study selection process followed a systematic procedure adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure transparency and rigor. The initial identification stage was conducted using predefined keyword combinations across selected databases, yielding a total of 38 records. After removing 14 duplicate entries, 24 unique articles remained and were considered eligible for further analysis. Given that the dataset was predefined and curated based on relevance to sustainability-oriented learning, biology education, and 21st-century skills, all 24 articles were retained without further exclusion at the full-text stage. These studies consist of systematic reviews, bibliometric analyses, and empirical studies focusing on Education for Sustainable Development (ESD), biology education, and related pedagogical approaches. The selected articles represent recent developments in the field (2019–2024), ensuring both relevance and recency. Thus, the final dataset included n = 24 articles, which formed the basis for subsequent data extraction and thematic analysis. This approach ensures that the synthesis is grounded in a focused yet representative body of literature

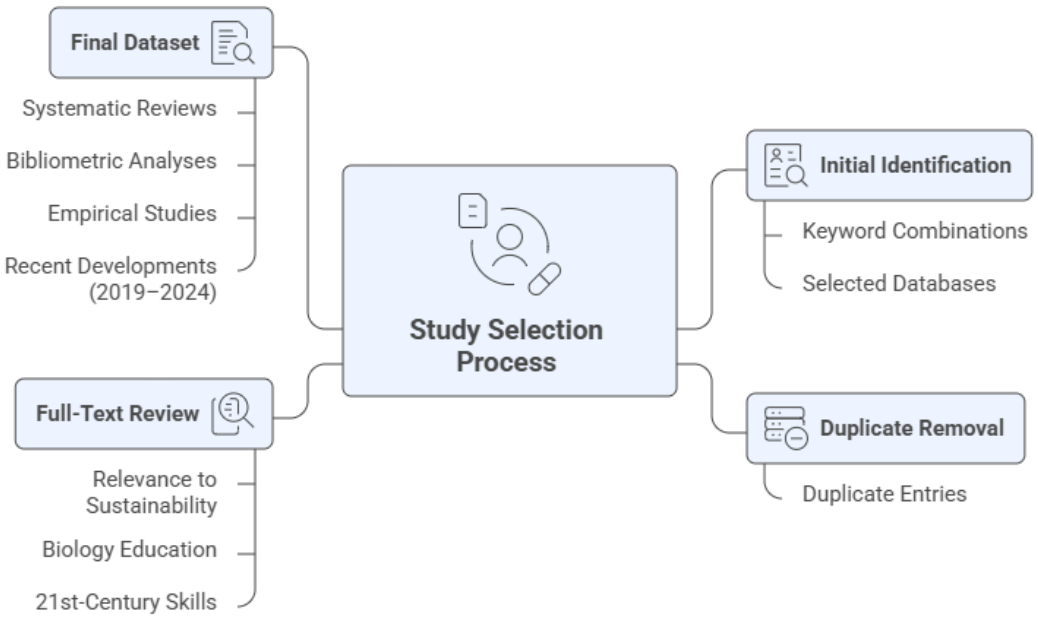

Figure 1. Study Selection Process

Data Extraction

Data from the selected studies were extracted using a structured data extraction matrix to ensure consistency, transparency, and comparability across studies. Each article was systematically

coded based on several analytical dimensions, including: (1) author(s) and publication year; (2) type of study (e.g., systematic review, bibliometric analysis, or empirical research); (3) educational context (e.g., biology education, science education, or teacher education); (4) instructional or conceptual focus (e.g., Education for Sustainable Development, STEM/STEAM, critical thinking integration, or digital learning); and (5) reported outcomes related to 21st-century skills, particularly critical thinking, creativity, and collaboration. The extraction process was conducted iteratively to ensure accuracy and reduce bias, with each study reviewed multiple times to verify the completeness of the extracted data. This structured approach enabled the identification of cross-cutting themes and facilitated comparison between different types of studies, particularly in terms of how sustainability-oriented learning is conceptualized and implemented within biology education contexts.

Data Analysis

The extracted data were analyzed using a thematic synthesis approach to identify patterns, relationships, and dominant research trends across the selected studies. The analysis began with open coding, where key concepts and findings from each article were categorized into three primary themes aligned with the study objectives: (1) critical thinking, (2) creative thinking, and (3) collaborative skills. Subsequently, axial coding was conducted to explore relationships between thematic categories and instructional approaches. The analysis revealed that studies focusing on ESD and sustainability frameworks predominantly emphasized the development of critical thinking and sustainability awareness, while studies integrating STEM, ICT, or innovative pedagogies highlighted creativity and collaboration as key outcomes. To strengthen the empirical basis of the analysis, a descriptive quantification was also applied. Of the 24 studies analyzed, 18 studies (75%) emphasized critical thinking, 15 studies (62.5%) highlighted creativity, and 13 studies (54.2%) addressed collaboration skills. The final stage involved synthesizing these findings into an integrated interpretation that explains how sustainability-oriented biology learning contributes to the development of multiple dimensions of 21st-century skills. This approach ensures that the analysis moves beyond description toward a more structured and evidence-based understanding of the research field.

Trustworthiness and Rigor

To ensure the validity and reliability of the review, several strategies were applied. First, the use of multiple databases enhanced the comprehensiveness of the literature search. Second, clear inclusion and exclusion criteria ensured the consistency of study selection. Third, systematic data extraction and thematic analysis minimized bias in interpreting findings. Finally, the transparent documentation of each stage of the review process improved the reproducibility and credibility of the study.

RESULTS

Overview of Selected Studies

A total of 24 studies were included in this review following a systematic selection process. These studies encompass systematic literature reviews, bibliometric analyses, and empirical investigations, providing a comprehensive and multi-layered understanding of sustainability-oriented learning in biology and science education. The predominance of review-based and bibliometric studies indicates that the field is still evolving at a conceptual level, while empirical

validation, although emerging, remains relatively limited. The selected studies were conducted across diverse contexts, including biology education, science education, and teacher education, reflecting the inherently interdisciplinary nature of Education for Sustainable Development (ESD). Across these contexts, a range of instructional approaches was identified, including ESD-based learning, socioscientific issues (SSI), STEM/STEAM integration, inquiry-based learning, project-based learning, and technology-enhanced instruction such as augmented reality (AR) and interactive laboratories. While these approaches share a common emphasis on contextual, problem-oriented, and student-centered learning, they differ in their pedagogical orientation and mechanisms of action. To enable systematic comparison, the extracted data were organized based on study characteristics, instructional focus, and targeted competencies. This structured categorization forms the basis for the analytical synthesis presented in the following sections.

Table 1. Summary of Selected Studies on Sustainability-Oriented Biology Learning and 21st-Century Skills (n = 24)

No	Author(s) & Year	Study Type	Context	Approach/ Focus	Skills Addressed	Key Findings
1	Raman et al. (2022)	SLR	Teacher Education	ESD integration	Critical thinking	ESD improves teacher readiness in sustainability pedagogy
2	Karampelas (2024)	Biblio metric	Science Education	Research trends	Critical thinking	Increasing focus on sustainability competencies
3	Ariza & Olatunde (2024)	SLR	Teacher Education	STEAM + Sustainability	Creativity, Collaboration	STEAM enhances interdisciplinary skills
4	Husamah et al. (2023)	SLR	Science Education	Environmental education	Critical thinking	Sustainability awareness increased
5	Prayogi & Verawati (2024)	Review	Physics Education	SDGs integration	Critical thinking	Tech integration supports analytical thinking
6	Corres et al. (2020)	SLR	Education	Sustainability competence	Critical thinking	Framework strengthens sustainability literacy
7	Hallinger & Nguyen (2020)	Biblio metric	Education	ESD research mapping	Critical thinking	Rapid growth of ESD research
8	Lestari & Suyanto (2024)	SLR	Science Education	Local wisdom	Creativity	Local context improves engagement

9	Suhendar et al. (2024)	Bibliometric	Science Education	Forecasting trends	Critical thinking	Emerging pedagogical innovation
10	Supriyadi et al. (2024)	Bibliometric	Science Learning	Phenomenon-based learning	Critical thinking	Contextual learning improves reasoning
11	Tiro et al. (2024)	Bibliometric	Science Education	Local wisdom mapping	Creativity	Cultural integration enhances creativity
12	Alberto et al. (2024)	SLR	Bio/Chemistry	Innovative strategies	Creativity, Collaboration	Active learning improves skills
13	Nurwidodo et al. (2023)	SLR	Science Learning	Pandemic learning	Collaboration	Digital learning enhances interaction
14	Subran & Mahmud (2024)	SLR	Biology Education	AR technology	Critical thinking	AR supports conceptual understanding
15	Fei et al. (2024)	SLR	STEM Education	STEM teaching	Critical thinking	STEM improves higher-order skills
16	Abdullah & Mahmud (2024)	SLR	STEM Education	TPACK	Creativity	Tech integration fosters innovation
17	Verawati & Purwoko (2024)	Review	Science Education	Interactive labs	Critical thinking	Simulation improves analysis
18	Wibowo et al. (2024)	Bibliometric	Physics Education	STEM challenges	Critical thinking	Need for adaptive pedagogy
19	Masykuri & Prayitno (2023)	Bibliometric	Science Education	SSI	Critical thinking	Socioscientific issues enhance reasoning
20	Puig & Jiménez (2022)	Book Chapter	Biology Education	Critical thinking	Critical thinking	Strong link with environmental literacy
21	Pessoa et al. (2024)	Empirical	Biology Education	Evolution literacy	Critical thinking	Improves sustainability awareness
22	Novidsa et al. (2020)	Empirical	Biology Education	ESD knowledge	Critical thinking	Teacher understanding still limited

23	Christodoulou & Papanikolaou (2023)	Qualitative	Teacher Education	ESD competence	Critical thinking	Enhances reflective thinking	
24	Rodríguez-Loinaz et al. (2024)	Empirical	Biology Education	ICT & citizen science	Collaboration	Promotes participatory learning	

Thematic Distribution and Evidence Profile

The synthesis reveals that critical thinking is the most consistently emphasized competency, identified in 18 out of 24 studies (75%), followed by creative thinking (62.5%) and collaborative skills (54.2%). However, these distributions should be interpreted in relation to the type and strength of evidence underpinning each finding. Empirical studies provide direct evidence of learning outcomes, particularly in terms of students' reasoning, engagement, and interaction. In contrast, systematic reviews and bibliometric analyses primarily offer conceptual insights and trend identification, without directly measuring student performance. This distinction indicates that while the prominence of critical thinking is strongly supported at a conceptual level, its empirical validation remains uneven across educational contexts. Furthermore, studies situated in teacher education highlight the importance of pedagogical readiness in implementing sustainability-oriented learning. While ESD frameworks are widely acknowledged, several studies point to gaps in teachers' understanding and application, suggesting that instructional effectiveness is closely tied to teacher competence. This reinforces the need to interpret learning outcomes within a broader ecosystem that includes both student and teacher dimensions.

Comparative Mapping of Instructional Approaches and Skills

To further examine how different pedagogical approaches contribute to specific competencies, a comparative mapping was conducted, as presented in Table 2.

Table 2. Mapping of Instructional Approaches and 21st-Century Skills

Approach	Critical Thinking	Creativity	Collaboration	Evidence Strength	Dominant Study Type
ESD-based learning	✓✓✓	✓	✓	High	SLR + Empirical
Socioscientific Issues (SSI)	✓✓✓	✓	✓	Moderate	Bibliometric + Review
STEM/STEAM	✓✓	✓✓✓	✓✓	High	SLR
Inquiry-based learning	✓✓✓	✓✓	✓	Moderate	SLR
Project-based learning	✓✓	✓✓✓	✓✓✓	High	Empirical
Technology-enhanced (AR, ICT)	✓✓	✓✓	✓✓✓	Moderate	Empirical + Review

Interpretation of Instructional Patterns

As shown in Table 2, the contribution of instructional approaches to 21st-century skills is differentiated rather than uniform across the reviewed studies. Approaches grounded in Education

for Sustainable Development (ESD) and socioscientific issues (SSI) demonstrate the strongest and most consistent association with critical thinking. This pattern can be explained by their emphasis on real-world problem analysis, ethical reasoning, and evidence-based decision-making, which require learners to engage in higher-order cognitive processes. These approaches situate learning within authentic contexts, encouraging students to evaluate complex issues, consider multiple perspectives, and construct reasoned arguments. As a result, critical thinking emerges not only as a learning outcome but also as an embedded process within sustainability-oriented instruction.

In contrast, STEM/STEAM and project-based learning approaches show a stronger alignment with creativity and collaboration. These approaches emphasize interdisciplinary integration, design-based thinking, and active student participation, allowing learners to explore problems from multiple disciplinary perspectives. Through project-oriented tasks, students are encouraged to generate innovative ideas, test possible solutions, and refine their understanding through iterative processes. At the same time, collaboration becomes essential, as students work together to negotiate meaning, share responsibilities, and co-construct knowledge. Notably, project-based learning appears as the most balanced approach, contributing significantly across all three skill domains, including critical thinking, creativity, and collaboration, making it particularly relevant for sustainability-oriented learning contexts.

Meanwhile, technology-enhanced learning environments, including augmented reality (AR) and ICT-based instruction, are more strongly associated with collaboration and engagement than with higher-order cognitive outcomes. These environments facilitate interaction, visualization, and access to diverse information sources, which can support collaborative learning processes and increase student motivation. However, their contribution to critical thinking appears less consistent across studies, suggesting that technology alone does not guarantee deeper cognitive engagement. Without appropriate pedagogical structuring, such as inquiry-based or problem-based frameworks, technology risks becoming a tool for content delivery rather than a means of fostering analytical reasoning. This indicates that the effectiveness of technology-enhanced learning depends heavily on its integration within well-designed instructional strategies.

Overall, this mapping not only summarizes the distribution of instructional approaches but also reveals that sustainability-oriented learning operates through multiple pedagogical pathways rather than a single unified model. Each approach contributes differently depending on its underlying instructional design, learning context, and targeted competencies. This finding highlights the importance of aligning pedagogical strategies with specific learning objectives to maximize their impact. Rather than relying on a single method, effective sustainability-oriented education requires a combination of approaches that collectively support the development of critical thinking, creativity, and collaboration. Such alignment ensures that learning experiences are both meaningful and adaptable to the complex demands of 21st-century education.

Underlying Mechanisms of Skill Development

The differentiated patterns observed across studies can be explained through several underlying pedagogical mechanisms that shape how students engage with sustainability-oriented learning. Problem-oriented learning, which characterizes Education for Sustainable Development (ESD) and socioscientific issues (SSI) approaches, plays a central role in promoting critical thinking. These approaches require students to analyze complex and often ambiguous real-world issues, evaluate multiple sources of evidence, and consider alternative perspectives before arriving

at reasoned conclusions. Such processes stimulate higher-order cognitive engagement and encourage reflective judgment. In addition, inquiry-based learning reinforces this mechanism by involving students in systematic investigation, hypothesis testing, and evidence-based reasoning, thereby strengthening their analytical capacity and deepening conceptual understanding within authentic learning contexts.

Creative thinking, on the other hand, is primarily fostered through project-based and interdisciplinary learning environments that emphasize active knowledge construction and innovation. In these settings, students are required to design solutions, generate original ideas, and explore multiple possibilities in response to sustainability-related challenges. This process encourages flexibility in thinking and supports the development of creative problem-solving skills. At the same time, collaborative skills emerge naturally within interactive learning environments that involve group discussion, negotiation, and shared decision-making. Such collaboration is particularly evident in technology-supported contexts, including digital platforms and citizen science initiatives, where students engage collectively in problem-solving processes and co-construct knowledge through continuous interaction and feedback.

Importantly, the integration of sustainability contexts enhances these pedagogical mechanisms by situating learning within authentic, meaningful, and socially relevant problems. This contextualization increases student engagement and facilitates the transfer of knowledge to real-life situations. However, the effectiveness of these mechanisms is not automatic and depends on several critical factors. Instructional quality, teacher competence, and the alignment between pedagogical strategies and intended learning outcomes play a decisive role in determining the success of sustainability-oriented learning. Without careful design and implementation, even well-established approaches may fail to produce meaningful improvements in 21st-century skills, highlighting the need for a coherent and well-supported instructional framework.

Cross-Study Trends and Implications

Several cross-study trends can be identified from the reviewed literature, reflecting the evolving direction of sustainability-oriented education. First, there is a clear shift from traditional content-based instruction toward contextual and problem-oriented learning, which emphasizes real-world relevance and student engagement. This transition aligns with the growing recognition that learning should not only transmit knowledge but also develop the capacity to apply it in complex situations. Second, the increasing integration of technology and interdisciplinary approaches highlights the transformation of science and biology education in the digital era. These approaches enable learners to connect concepts across disciplines while utilizing digital tools to explore and solve problems. Third, the growing emphasis on sustainability competencies indicates that education is increasingly positioned as a strategic pathway for addressing global environmental and societal challenges.

Despite these advancements, several challenges remain that may limit the effectiveness of sustainability-oriented learning. A recurring issue identified across studies is the limited readiness of teachers to implement ESD principles in classroom practice. While theoretical frameworks and policy support for sustainability education are well established, their translation into instructional practice is often inconsistent. This gap suggests that teachers may lack sufficient pedagogical knowledge, training, or institutional support to effectively integrate sustainability concepts into teaching. As a result, the success of sustainability-oriented learning depends not only on curriculum

innovation but also on the development of teacher competence. Strengthening professional development and providing continuous support are therefore essential to ensure meaningful implementation.

The findings demonstrate that sustainability-oriented biology learning provides a strong and relevant foundation for developing 21st-century skills, particularly critical thinking, creativity, and collaboration. However, its effectiveness is contingent upon the strategic alignment of instructional design, learning context, and targeted competencies. No single pedagogical approach can fully address all dimensions of these skills, indicating the need for integrative and flexible instructional strategies. This highlights the importance of combining multiple approaches to create comprehensive learning experiences that are responsive to both educational goals and real-world demands. Such alignment is essential for ensuring that sustainability education contributes effectively to preparing learners for future challenges.

DISCUSSION

The findings of this review confirm that sustainability-oriented learning, particularly within the framework of Education for Sustainable Development (ESD), plays a significant role in fostering 21st-century skills, with critical thinking emerging as the most dominant outcome. This result is consistent with previous research emphasizing that ESD requires learners to engage with complex, real-world problems that demand analytical reasoning and reflective judgment (Wu & Shen, 2016; O'Flaherty & Liddy, 2018). Within biology education, this relevance becomes even more pronounced, as the discipline inherently deals with ecological systems and sustainability challenges (Nurse, 2016). Consequently, sustainability-oriented learning is not merely an instructional innovation but a necessary pedagogical response to contemporary global issues, positioning education as a critical driver for developing informed and responsible future citizens.

A closer examination of the findings reveals that the effectiveness of sustainability-oriented learning is strongly influenced by the instructional approaches employed. Approaches such as socioscientific issues (SSI) and inquiry-based learning demonstrate a strong contribution to critical thinking due to their emphasis on argumentation and evidence evaluation. This is supported by studies highlighting that sustainability learning is most effective when situated at the interface of science and society, where students are required to engage with authentic dilemmas and competing perspectives (Tassone et al., 2022). In contrast, project-based and problem-based learning approaches contribute more broadly to creativity and collaboration, as they involve active knowledge construction and teamwork. These findings align with research indicating that PBL and PjBL are particularly effective for sustainability education due to their emphasis on real-world problem-solving and interdisciplinary integration (Cörvers et al., 2016).

The role of technology in sustainability-oriented learning presents a more complex dynamic. While digital tools, including augmented reality and online platforms, enhance engagement and facilitate collaborative learning, their impact on higher-order thinking remains inconsistent. This suggests that technology functions primarily as a mediating tool rather than a determinant of learning outcomes. Previous studies similarly indicate that the effectiveness of digital learning environments depends on how they are pedagogically structured rather than on the technology itself (Ismail et al., 2024). Without integration into inquiry-based or problem-oriented frameworks, technology risks reinforcing surface-level engagement rather than deep learning.

Therefore, the success of technology-enhanced sustainability education lies in its alignment with pedagogical principles that promote critical inquiry and meaningful interaction.

From a theoretical perspective, these findings can be understood through constructivist and sustainability learning frameworks, which emphasize active engagement and contextual learning. Sustainability-oriented learning is most effective when students are involved in authentic, experiential processes that connect knowledge with real-world applications. This is supported by research highlighting the importance of outdoor, contextual, and experiential approaches in biology and sustainability education (Jeronen et al., 2016). Furthermore, curriculum-level integration of sustainability has been shown to shape not only cognitive outcomes but also students' values and attitudes toward sustainability (Fröberg et al., 2023). These perspectives reinforce the idea that learning is not merely cognitive but also social and contextual, requiring meaningful interaction with real-life issues.

Despite these strengths, the findings also reveal persistent challenges, particularly in relation to teacher readiness and implementation. While sustainability frameworks are well established conceptually, their practical application in classrooms remains uneven. Several studies indicate that teachers often lack the necessary pedagogical knowledge and training to effectively integrate ESD into instruction (O'Flaherty & Liddy, 2018; Ismail et al., 2024). This gap highlights the importance of professional development and institutional support in ensuring the successful implementation of sustainability-oriented learning. Without adequate preparation, there is a risk that ESD will be implemented superficially, limiting its potential impact on student learning and skill development.

In addition, the uneven distribution of empirical evidence highlights the need for more robust research. While bibliometric and review studies provide valuable insights into trends and conceptual frameworks (Abdullah, 2022), fewer studies offer direct evidence of learning outcomes in classroom settings. Empirical studies, such as those examining project-based learning in sustainability contexts, demonstrate promising results in improving critical thinking and engagement (Rahmayanti et al., 2021; Carrió Llach & Llerena Bastida, 2023). However, these studies remain limited in scope and context. Future research should therefore focus on experimental and longitudinal designs to better understand the long-term impact of sustainability-oriented learning across diverse educational settings.

Overall, this study contributes to the growing body of literature by providing a structured and comparative analysis of sustainability-oriented learning in biology education. The findings highlight that effective sustainability education requires a strategic alignment between instructional approaches, learning contexts, and targeted competencies. Rather than relying on a single pedagogical model, an integrative approach that combines ESD, inquiry, project-based learning, and technology is more likely to produce meaningful outcomes. This reinforces the view that sustainability-oriented learning is inherently multidimensional and must be designed holistically to address the complex demands of 21st-century education.

CONCLUSION

This study provides a systematic and analytical synthesis of how sustainability-oriented biology learning contributes to the development of 21st-century skills. The findings demonstrate that sustainability-based approaches, particularly those grounded in Education for Sustainable

Development (ESD), play a significant role in fostering critical thinking, creativity, and collaboration. Among these competencies, critical thinking emerges as the most consistently emphasized outcome, reflecting the problem-oriented and contextual nature of sustainability learning. The study further reveals that different instructional approaches contribute to different skill domains. ESD and socioscientific approaches are more strongly associated with critical thinking, while project-based and STEM-oriented learning support creativity and collaboration. This indicates that sustainability-oriented learning operates through multiple pedagogical pathways rather than a single unified model. Therefore, effective implementation requires a strategic integration of various instructional approaches to address diverse learning objectives. However, the effectiveness of sustainability-oriented learning is influenced by several factors, including instructional design, teacher competence, and contextual alignment. The findings highlight that the successful development of 21st-century skills depends not only on the choice of learning approach but also on how it is implemented in practice. In addition, the limited number of empirical studies suggests the need for more rigorous research to strengthen the evidence base. In conclusion, sustainability-oriented biology learning offers a relevant and powerful framework for preparing students to address complex global challenges. Its successful implementation requires an integrative, flexible, and context-sensitive approach that aligns pedagogical strategies with the demands of 21st-century education.

ADDITIONAL INFORMATION

Section	Description
Funding	This study did not receive any financial support from external organizations or funding agencies.
Conflict of Interest	The authors confirm that there are no conflicts of interest related to this publication.
Author Contributions	All authors were actively involved in the research process. The first author was responsible for conceptual development, methodological design, data analysis, and manuscript preparation. The second author contributed to data validation, analysis, and manuscript revision. The third author provided supervision and critical review of the manuscript. All authors have read and approved the final version.
Data Availability	The datasets generated and/or analyzed during the current study can be obtained from the corresponding author upon reasonable request.
Ethical Approval	The research was conducted in accordance with established ethical guidelines. Participation was voluntary, and all data were collected anonymously to ensure confidentiality.
AI Usage Statement	Artificial intelligence tools were utilized solely for linguistic refinement. All research processes, analyses, and conclusions were carried out independently by the authors.

REFERENCES

Abdullah, A., & Mahmud, S. N. D. (2024). Applying TPACK in STEM education towards 21st century: Systematic literature review. *International Journal of Academic Research in Progressive Education and Development, 13*(1), 1014–1032. http://dx.doi.org/10.6007/IJARPED/v13-i1/20667

Abdullah, K. H. (2022). Publication trends in biology education: A bibliometric review of 63 years. *Journal of Turkish Science Education, 19*(2), 465–480. https://doi.org/10.36681/tused.2022.131

Alberto, M. C. L., Viviana, B. V. C., Vladimir, B. E. C., & Fernanda, P. A. P. (2024). Innovative strategies to strengthen teaching-researching skills in chemistry and biology education: A systematic literature review. *Frontiers in Education, 9*, 1363132. https://doi.org/10.3389/feduc.2024.1363132

Ariza, J. Á., & Olatunde-Aiyedun, T. G. (2024). A systematic literature review on STEAM pre- and in-service teacher education for sustainability: Are teachers ready? *Eurasia Journal of Mathematics, Science and Technology Education, 20*(9), em2498. https://doi.org/10.29333/ejmste/14982

Carrió Llach, M., & Llerena Bastida, M. (2023). Exploring innovative strategies in problem-based learning to contribute to sustainable development: A case study. *International Journal of Sustainability in Higher Education, 24*(9), 159–177. https://doi.org/10.1108/IJSHE-07-2021-0296

Christodoulou, P., & Papanikolaou, A. (2023). Examining pre-service teachers' critical thinking competences within the framework of education for sustainable development: A qualitative analysis. *Education Sciences, 13*(12), 1187. https://doi.org/10.3390/educsci13121187

Corres, A., Rieckmann, M., Espasa, A., & Ruiz-Mallén, I. (2020). Educator competences in sustainability education: A systematic review of frameworks. *Sustainability, 12*(23), 9858. https://doi.org/10.3390/su12239858

Cörvers, R., Wiek, A., de Kraker, J., Lang, D. J., & Martens, P. (2016). Problem-based and project-based learning for sustainable development. In H. Heinrichs, P. Martens, G. Michelsen, & A. Wiek (Eds.), *Sustainability science* (pp. xx–xx). Springer. https://doi.org/10.1007/978-94-017-7242-6_29

Dara, N. D. D. (2024). Education for sustainable development (ESD) climate-based in biology education. *Proceeding International Conference on Digital Education and Social Science, 2*(1), 332–338. https://doi.org/10.55506/icdess.v2i1.85

Ekamilasari, E., & Pursitasari, I. D. (2021). Students' critical thinking skills and sustainability awareness in science learning for implementation education for sustainable development. *Indonesian Journal of Multidisciplinary Research, 1*(1), 121–124. https://doi.org/10.17509/ijomr.v1i1.33792

Fathurohman, I., Amri, M. F., & Septiyanto, A. (2023). Integrating STEM-based education for sustainable development (ESD) to promote quality education: A systematic literature review. *Jurnal Penelitian Pendidikan IPA, 9*(11), 1052–1059. https://doi.org/10.29303/jppipa.v9i11.4430

Fatimah, F. N. U., Siswanto, J., Nuroso, H., & Hayat, M. S. (2023). Implementation of the education for sustainable development (ESD)-based predict, observe, and explain (POE) learning module to improve critical thinking skills. *Practice of The Science of Teaching Journal: Jurnal Praktisi Pendidikan, 2*(2), 52–63. https://doi.org/10.58362/hafecspost.v2i2.32

Fei, L., Yunus, M. M., Haibin, T., & Fan, C. (2024). A systematic review of STEM teaching in higher education (2014–2023). *International Journal of Academic Research in Progressive Education and Development, 13*(3), 3217–3241. http://dx.doi.org/10.6007/IJARPED/v13-i3/22296

Francisco, R., Ibrohim, I., & Susilo, H. (2024). Fostering communication and collaboration skills in biology education through problem-oriented project-based learning (POPBL). *Jurnal Biolokus: Jurnal Penelitian Pendidikan Biologi dan Biologi, 7*(2), 226–236. http://dx.doi.org/10.30821/biolokus.v7i2.3866

Fröberg, A., Wiklander, P., & Lundvall, S. (2023). Sustainability-oriented learning in physical education and health (PEH): A document analysis of the Swedish syllabi. *Curriculum Studies in Health and Physical Education, 14*(3), 340–356. https://doi.org/10.1080/25742981.2022.2112921

Fuadiyah, M. L., Norra, B. I., & Astutik, F. (2022). Biology learning model to improve critical thinking skills of tenth-grade students: A meta-analysis. *Assimilation: Indonesian Journal of Biology Education, 5*(2), 101–112. https://doi.org/10.17509/aijbe.v5i2.46084

González-Gómez, D., & Jeong, J. S. (2022). Approaches and methods of science teaching and sustainable development. *Sustainability, 14*(3), 1546. https://doi.org/10.3390/su14031546

Hallinger, P., & Nguyen, V. T. (2020). Mapping the landscape and structure of research on education for sustainable development: A bibliometric review. *Sustainability, 12*(5), 1947. https://doi.org/10.3390/su12051947

Hogan, D., & O'Flaherty, J. (2021). Addressing education for sustainable development in the teaching of science: The case of a biological sciences teacher education program. *Sustainability, 13*(21), 12028. https://doi.org/10.3390/su132112028

Husamah, H., Suwono, H., Nur, H., Dharmawan, A., & Chang, C. Y. (2023). The existence of environmental education in the COVID-19 pandemic: A systematic literature review. *Eurasia Journal of Mathematics, Science and Technology Education, 19*(11). https://doi.org/10.29333/ejmste/13668

Ismail, I., Riandi, R., Kaniawati, I., Permanasari, A., Sopandi, W., & Supriyadi, S. (2024). Education for sustainable development in secondary school: A review and bibliometric analysis. *KnE Social Sciences*, 1270–1280. https://doi.org/10.18502/kss.v9i13.16069

Jeronen, E., Palmberg, I., & Yli-Panula, E. (2016). Teaching methods in biology education and sustainability education including outdoor education for promoting sustainability: A literature review. *Education Sciences, 7*(1), 1. https://doi.org/10.3390/educsci7010001

Karampelas, K. (2024). Teacher training in science education: Insights into research trends through a bibliometric approach. In *Bibliometrics—An essential methodological tool for research projects*. IntechOpen. https://doi.org/10.5772/intechopen.1005273

Kurniawan, A., Jumadi, J., Kuswanto, H., & Syar, N. I. (2024). The 21st-century education: A systematic literature review of transforming learning methods to foster critical thinking skills through augmented reality in science learning. *Jurnal Eduscience, 11*(3), 601–622. https://doi.org/10.36987/jes.v11i3.6438

Lestari, N., & Suyanto, S. (2024). A systematic literature review about local wisdom and sustainability: Contribution and recommendation to science education. *Eurasia Journal of Mathematics, Science and Technology Education, 20*(2), em2394. https://doi.org/10.29333/ejmste/14152

Masykuri, M., & Prayitno, B. A. (2023). Research trend of socioscientific issues based on Scopus journal database: A bibliometric study from 2011 to 2021. *Jurnal Penelitian Pendidikan IPA, 9*(8), 417–423. https://doi.org/10.29303/jppipa.v9i8.3155

Novidsa, I., Purwianingsih, W., & Riandi, R. (2020). Exploring knowledge of prospective biology teacher about education for sustainable development. *Jurnal Pendidikan Biologi Indonesia, 6*(2), 317–326. https://doi.org/10.22219/jpbi.v6i2.12212

Nurse, P. (2016). The importance of biology education. *Journal of Biological Education, 50*(1), 7–9. https://doi.org/10.1080/00219266.2016.1140985

Nurwidodo, N., Ibrohim, I., Sueb, S., & Husamah, H. (2023). "Let's transform!": A systematic literature review of science learning in COVID-19 pandemic era. *Eurasia Journal of Mathematics, Science and Technology Education, 19*(2), em2224. https://doi.org/10.29333/ejmste/12875

O'Flaherty, J., & Liddy, M. (2018). The impact of development education and education for sustainable development interventions: A synthesis of the research. *Environmental Education Research, 24*(7), 1031–1049. https://doi.org/10.1080/13504622.2017.1392484

Pessoa, P., Lopes, J. B., de Lima, J., et al. (2024). Evolutionary literacy as a catalyst for sustainable futures: Connecting biological evolution education and education for sustainability. *Evolution: Education and Outreach, 17*, 22. https://doi.org/10.1186/s12052-024-00213-0

Prayogi, S., & Verawati, N. N. S. P. (2024). Physics learning technology for sustainable development goals (SDGs): A literature study. *International Journal of Ethnoscience and Technology in Education, 1*(2), 155–191. https://doi.org/10.33394/ijete.v1i2.12316

Puig, B., & Jiménez-Aleixandre, M. P. (2022). The integration of critical thinking in biology and environmental education: Contributions and further directions. In B. Puig & M. P. Jiménez-Aleixandre (Eds.), *Critical thinking in biology and environmental education* (pp. xx–xx). Springer. https://doi.org/10.1007/978-3-030-92006-7_15

Rahmayanti, E., Hendayana, S., & Riandi, R. (2021). Project-based learning in pandemic COVID-19: The implementation of ESD to develop students' critical thinking skills. *Unnes Science Education Journal, 10*(3), 137–144. https://doi.org/10.15294/usej.v10i3.46738

Raman, F. I., Hutagalung, F. D., & Rahman, M. N. A. (2022). Preparing pre-service teachers for integration of education for sustainable development in school: A systematic review (2013–2022). *Geografia, 18*(3), 153–169. https://doi.org/10.17576/geo-2022-1803-10

Rodríguez-Loinaz, G., Ametzaga-Arregi, I., & Palacios-Agundez, I. (2024). ICT tools and citizen science: A pathway to promote science learning and education for sustainable development in schools. *Journal of Biological Education, 58*(3), 609–625. https://doi.org/10.1080/00219266.2022.2092192

Saragih, L., Riandi, R., & Solihat, R. (2021). The implementation of education for sustainable development into biology learning to equip students with systemic thinking and problem-solving skills. *Journal of Physics: Conference Series, 1806*(1), 012158. https://doi.org/10.1088/1742-6596/1806/1/012158

Setiyaningsih, L. B., Riandi, R., Amprasto, A., & Mardiyah, M. (2024). Application of inquiry-based learning with education for sustainable development to enhance critical thinking skills and sustainability awareness. *Jurnal Penelitian Pendidikan IPA, 10*(10), 7790–7802. https://doi.org/10.29303/jppipa.v10i10.8943

Subran, S., & Mahmud, S. N. D. (2024). Augmented reality (AR) technology in biology and life science education: A systematic literature review. *International Journal of Academic Research in Progressive Education and Development, 13*(1), 768–792. http://dx.doi.org/10.6007/IJARPED/v13-i1/20455

Suhendar, S., Widodo, A., Solihat, R., & Riandi, R. (2024). Forecasting methods in science education: A bibliometric analysis using the Scopus database. *KnE Social Sciences, 9*(19), 472–483. https://doi.org/10.18502/kss.v9i19.16535

Supriyadi, S., Suhandi, A., Samsudin, A., Setiawan, A., Susilawati, A., Isnawati, I., & Ismail, I. (2024). Analysis of Scopus articles on phenomenon-based learning through bibliometric analysis. *KnE Social Sciences*, 1301–1310. https://doi.org/10.18502/kss.v9i13.16072

Tassone, V. C., den Brok, P., Tho, C. W., & Wals, A. E. (2022). Cultivating students' sustainability-oriented learning at the interface of science and society: A configuration of interrelated enablers. *International Journal of Sustainability in Higher Education, 23*(8), 255–271. https://doi.org/10.1108/IJSHE-01-2022-0014

Tiro, A. R., Surtikanti, H. K., & Hidayat, F. A. (2024). Local wisdom in science education using bibliometric mapping and VOSviewer. *KnE Social Sciences*, 1338–1354. https://doi.org/10.18502/kss.v9i13.16074

Usman, A., Munandar, K., & Utomo, A. P. (2024). How can problem-based learning promote critical thinking skills in biology? A systematic literature review in reputable journals. *Research and Development in Education (RaDEn), 4*(1), 450–464. https://doi.org/10.22219/raden.v4i1.32401

Verawati, N. N. S. P., & Purwoko, A. A. (2024). Literature review on the use of interactive labs technology in the context of science education. *International Journal of Ethnoscience and Technology in Education, 1*(1), 76–96. https://doi.org/10.33394/ijete.v1i1.12154

Welter, V. D. E., Emmerichs-Knapp, L., & Krell, M. (2023). Are we on the way to successfully educating future citizens? A spotlight on critical thinking skills and beliefs about the nature of science among pre-service biology teachers in Germany. *Behavioral Sciences, 13*(3), 279. https://doi.org/10.3390/bs13030279

Wu, Y. C. J., & Shen, J. P. (2016). Higher education for sustainable development: A systematic review. *International Journal of Sustainability in Higher Education, 17*(5), 633–651. https://doi.org/10.1108/IJSHE-01-2015-0004

Yli-Panula, E., Jeronen, E., Lemmetty, P., & Pauna, A. (2018). Teaching methods in biology promoting biodiversity education. *Sustainability, 10*(10), 3812. https://doi.org/10.3390/su10103812