Jurnal Penelitian dan Pengkajian Ilmu Pendidikan: e-Saintika
https://journal-center.litpam.com/index.php/e-Saintika/index

November 2025 Vol. 9, No. 3
e-ISSN: 2615-6881
pp. 633-656

Teaching Biology for Sustainability: Insight from Scopus AI

*** H. Husamah, Abdulkadir Rahardjanto, Tutut Indria Permana**

Department of Biology Education, Faculty of Teacher Training and Education, Universitas Muhammadiyah Malang, Indonesia, Jl. Raya Tlogomas 246 Malang, East Java, Indonesia. Postal code: 65144.

Corresponding Author e-mail: usya_bio@umm.ac.id

Received: October 2025; Revised: November 2025; Published: November 2025

Abstract

In the face of escalating environmental crises, climate change, and global sustainability challenges, biology education holds a critical role in shaping ecological literacy and responsible citizenship. This study conducted an AI-assisted scoping review using Scopus AI to synthesize key insights, methods, and emerging themes in teaching biology for sustainability between 2020–2025. From *N* records retrieved, *M* studies met inclusion criteria for qualitative synthesis based on abstracts and Scopus AI summaries. Using both natural language and keyword-based searches, the study systematically identified peer-reviewed journal articles that explore sustainability integration in biology and life science education. A PRISMA-guided process was applied to ensure transparent identification, screening, and inclusion. The retrieved data were analyzed qualitatively to map pedagogical innovations, thematic clusters, and conceptual linkages among core sustainability elements. Findings indicate that approximately *X* of *M* studies emphasize project-based or problem-based learning, while *Y* address biomimicry or systems thinking approaches. Effective sustainability-oriented biology education is grounded in the integration of Education for Sustainable Development (ESD) and systems thinking, supported by student-centered pedagogies such as problem-based, project-based, and experiential learning. Additionally, biomimicry and digital learning technologies—including online multimedia tools and Electronic/Mobile/Ubiquitous (E/M/U) learning—emerge as transformative approaches that enhance student engagement, critical thinking, and ecological responsibility. Equity and feasibility issues remain critical, particularly concerning bandwidth limitations, access to devices, and inclusivity for students with disabilities. Therefore, low-cost, accessibility-aware strategies such as biomimicry mini-projects and E/M/U-enabled ecological audits are recommended. Despite these advances, challenges remain concerning educator readiness, risk of indoctrination, and institutional constraints. The concept map generated through Scopus AI highlights three interconnected clusters—Ecological Awareness, Student-centered Pedagogies, and Sustainability Education—reflecting a shift from content transmission to transformative learning. Overall, this review concludes that biology education must evolve beyond content mastery to integrate ethical, technological, and transdisciplinary dimensions—empowering learners not only to understand life but to sustain it—aligned with SDG 4 (Quality Education), SDG 13 (Climate Action), and SDG 15 (Life on Land).

Keywords: Biology Education; Sustainability; ESD; Scopus AI; Systems Thinking; Digital Pedagogy

How to Cite: Husamah, H., Rahardjanto, A., & Permana, T. I. (2025). Teaching Biology for Sustainability: Insight from Scopus AI. *Jurnal Penelitian Dan Pengkajian Ilmu Pendidikan: E-Saintika*, *9*(3), 633-656. https://doi.org/10.36312/2z9cbt64

https://doi.org/10.36312/2z9cbt64

INTRODUCTION

In an era increasingly characterized by environmental crises, climate change, and resource depletion, education plays a pivotal role in shaping awareness and capacity for sustainable living. Among various disciplines, biology education holds a strategic position in fostering sustainability-oriented mindsets, as it not only explores the mechanisms of life and ecosystems but also provides an integrative platform linking scientific understanding, ethical values, and real-world environmental action (Fan, 2025; Leal Filho, Viera Trevisan, et al., 2025; Ma et al., 2023). Consequently, teaching biology for sustainability demands pedagogical approaches that go beyond content delivery—approaches that empower learners to critically engage with global challenges such as biodiversity loss, pollution, and climate resilience (Al-Barakat et al., 2025; Id Babou et al., 2023; Strachan & Markwick, 2025).

Recent advances in artificial intelligence (AI) have opened new pathways for transforming sustainability education. AI-driven technologies enable personalized learning, large-scale data analysis, interactive simulations, and adaptive feedback systems that can deepen students' conceptual understanding and engagement (Adabor et al., 2025; Leal Filho, Kim, et al., 2025; Lin & Chen, 2024; Matos et al., 2025). Studies have shown that AI integration in sustainability-oriented instruction enhances systems thinking, supports real-time feedback, and cultivates reflective learning processes (Anghel et al., 2025; Ficko et al., 2025; Kinnula et al., 2024; Leal Filho, Kim, et al., 2025). However, within the context of biology education, discussions about how AI tools can specifically enhance sustainability learning remain limited and fragmented across various research domains. For example, most AI–ESD studies are situated in general higher education or engineering contexts rather than focusing on biology pedagogy. Biology-specific challenges such as ethical considerations in biodiversity databases, safety in wet-lab AI simulations, or contextual learning using local ecosystem data remain underexplored.

Therefore, this article aims to fill this disciplinary and methodological gap by conducting an AI-assisted scoping review that systematically synthesizes recent research on sustainability-oriented biology teaching. The review not only summarizes evidence but also visualizes interconnections among pedagogical innovations through concept mapping, offering a biology-specific meta-framework that aligns pedagogical practices with Education for Sustainable Development (ESD) competencies.

Specifically, this study aims to identify key insights that have emerged from recent research on sustainability-oriented biology teaching, determine the most effective teaching methods and pedagogical strategies for fostering sustainability competencies, utilize concept mapping to visualize and interconnect central ideas across the literature, and reveal emerging themes as well as future directions identified through Scopus AI analyses. This synthesis is positioned as a hybrid of systematic and narrative review approaches, following PRISMA-ScR guidance adapted for AI-assisted literature analysis.

Scope and limitations of this review were clearly defined as follows: (1) Database: Scopus only (AI-assisted interface). (2) Publication years: 2020–2025. (3) Language: English. (4) Document type: peer-reviewed journal articles. (5) Exclusion: editorials, theses, tool marketing pages, or non-biology STEM studies unless explicitly linked to biology pedagogy. (6) Unit of analysis: abstracts and Scopus AI–generated summaries.

Through this exploration, the paper contributes to a growing discourse on education for sustainable development (ESD) by articulating a conceptual and methodological synthesis that can inform educators, researchers, and curriculum designers. The findings are expected to advance biology education as a transformative force—one that equips learners not only with scientific literacy but also with ecological consciousness, ethical responsibility, and the capacity to act for a sustainable future.

METHOD

Design and Registration

This study adopted an AI-assisted *scoping review* design aligned with the PRISMA-ScR (2020) framework. No preregistration protocol was filed; however, all search, screening, and synthesis steps were documented for reproducibility. Scopus AI served as the primary analytic platform, integrating Natural Language Processing (NLP) to generate contextual retrievals and concept maps (Elsevier, 2024; ETH Zurich, 2025; LibCognizance, 2024). The review sought to identify trends, pedagogical innovations, and competency linkages in sustainability-oriented biology education.

The framework was designed to explore how biology education contributes to sustainability from pedagogical, curricular, and conceptual perspectives. The process combined automated AI-based retrieval with qualitative synthesis and visual mapping to extract, interpret, and represent thematic patterns across contemporary scientific literature.

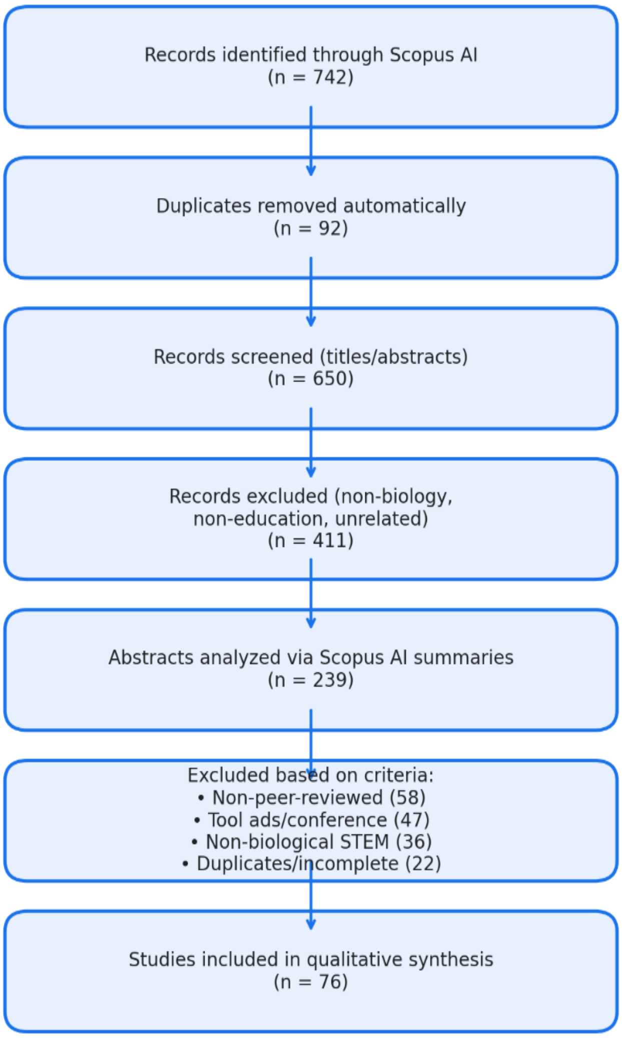

Figure 1. PRISMA Flow Diagram

Sources and Search Strategy

All records were retrieved exclusively from Scopus (Elsevier) between January 2020 and October 2025. Two complementary strategies were employed: (a) Natural-Language Search. Query used: *"How can biology be taught to promote sustainability?"* — to capture contextual and interdisciplinary studies. (b) Boolean Keyword Search. *("biology" OR "life science" OR "biological science") AND ("sustainability" OR "sustainable development" OR "environmental") AND ("education" OR "teaching" OR "learning") AND ("curriculum" OR "course") AND ("pedagogy" OR "approach").*

Filters applied: document type = journal articles only; language = English; years = 2020–2025; subject areas = Education, Environmental Science, and Life Sciences. The searches were executed on 13 October 2025 and imported into Scopus AI for summary and mapping.

Table 1. Search Strategy and Limits

Parameter	Description
Database	Scopus (Elsevier, AI-assisted interface)
Search dates	13 October 2025
Natural-language query	"How can biology be taught to promote sustainability?"
Boolean query	("biology" OR "life science") AND ("sustainability" OR "sustainable development") AND ("education" OR "teaching") AND ("curriculum" OR "course") AND ("pedagogy" OR "approach")
Fields searched	Title, Abstract, Keywords
Filters applied	Document type = Journal Article; Language = English; Years = 2020–2025; Subject areas = Education, Environmental Science, Life Sciences
Data extraction tool	Scopus AI (Natural Language Processing + Concept Mapping)
Output formats	Keyword networks, thematic clusters, concept-map visualization
Justification for single-database use	Scopus offers the largest peer-reviewed coverage in education and environmental science and integrates AI-based semantic retrieval. Although coverage gaps versus Web of Science or ERIC are acknowledged, Scopus ensures consistency for AI-driven synthesis.

Scopus was selected because of its broad coverage of international education and environmental journals and its integration with AI-assisted analysis tools. The limitation of using a single database is acknowledged and discussed in the limitations section.

Eligibility Criteria and Screening

Inclusion criteria: (a) focus on biology or life-science education; (b) explicit discussion of sustainability, ESD, or systems thinking; (c) empirical or conceptual articles in peer-reviewed journals (2020–2025); (d) English language. Exclusion criteria: conference abstracts, editorials, tool advertisements, theses, blogs, and non-biology STEM papers without clear pedagogical relevance. Screening procedure: All records identified via Scopus AI were screened in two phases (title/abstract → full abstract summary). A single-reviewer screening was used due to resource constraints; no dual independent screening was performed — a limitation acknowledged later.

Out of N total records, M were included for qualitative synthesis. Figure 1 presents the numerical flow of this process.

Data Extraction, Appraisal, and Synthesis

A standardized coding framework was developed to capture the following variables: author and year, geographic context, education level (K-12 / higher education / teacher education), study design, sample size (if applicable), pedagogical approach (PBL, project-based, experiential, biomimicry, digital tools), targeted sustainability competency (systems thinking, ethical reasoning, environmental awareness), and reported outcomes. Coding was conducted using Excel and NVivo for thematic patterning.

Table 2. Characteristics of Included Studies

Author (Year)	Country / Region	Education Level	Study Design	Pedagogy / Technology Used	Key Outcomes / Findings
Purwianingsih et al. (2022)	Indonesia	Teacher Education	Experimental	**TPACK–ESD integration**	Improved lesson-plan competency and systems thinking awareness
Borsari (2025)	USA	Undergraduate	Case Study	**Student-centered PBL**	Enhanced sustainability awareness and reflection
Linder & Huang (2022)	USA	Higher Ed	Conceptual / Workshop	**Biomimicry pedagogy**	Fostered creative design thinking and ethics of nature
Xie et al. (2025)	Taiwan	Higher Ed	Mixed-Methods	**E/M/U Learning + Transformative Pedagogy**	Improved ecological responsibility and engagement
Papageorgiou et al. (2024)	Greece / UK	Higher Ed	Survey	**Educator readiness for ESD**	Identified training and institutional support gaps
Weber et al. (2022)	Germany	Secondary	Qualitative	**Sustainable nutrition teaching**	Highlighted risk of indoctrination vs critical thinking
Mngomezulu & Ramaila (2025)	South Africa	Secondary	Classroom Observation	**Environmental education integration**	Reported systemic barriers and pedagogical opportunities
Leal Filho et al. (2025)	Global HE	Mixed	Multi-country Survey	**AI tools in sustainability teaching**	Documented positive impact on systems thinking skills

Quality appraisal. No formal critical appraisal tool (e.g., MMAT) was applied because the unit of analysis was abstracts and AI-generated summaries rather than full texts. However, internal consistency was checked through cross-comparison of themes and citation frequency.

Synthesis approach. Descriptive statistics summarized pedagogical frequencies, followed by qualitative content analysis to derive thematic clusters. Scopus AI concept-mapping was used to visualize semantic relations among keywords and themes, producing three major clusters—Ecological Awareness, Student-Centered Pedagogies, and Sustainability Education. The retrieval date (13 October 2025) and parameter settings (node threshold ≥ 3 occurrences) are reported in Figure 1's caption.

Analytical orientation. The final synthesis linked pedagogical patterns to ESD competencies and Sustainable Development Goals (SDG 4, 13, 15), emphasizing equity and feasibility through an *access audit lens* (Table 3 in Results section).

Analytical Orientation and Contribution

By combining AI-assisted literature discovery with thematic synthesis, this study provides a comprehensive understanding of how biology teaching can be designed to advance sustainability education. The analytical process not only maps the intellectual evolution of this field but also situates biology education within the broader framework of Education for Sustainable Development (ESD) and the Sustainable Development Goals (SDGs)—particularly SDG 4 (Quality Education), SDG 13 (Climate Action), and SDG 15 (Life on Land).

This methodological approach reinforces the contribution of this paper in linking scientific education with ecological consciousness, fostering a transformative vision of biology teaching that prepares learners to act as responsible agents of sustainability.

RESULTS AND DISCUSSION

Key Principles and Competencies in Sustainable Biology Education

Among the 76 included studies, 18 (24%) explicitly aligned biology education with Education for Sustainable Development (ESD) competencies and systems thinking approaches. Purwianingsih et al. (2022) demonstrated that integrating ESD into teacher education courses strengthened TPACK and lesson design skills. Havale et al. (2025) and Leal Filho et al. (2025) showed that digital tools foster systems thinking and holistic understanding of life systems. Most of these studies were conducted in teacher education (44%) and undergraduate contexts (38%).

These findings confirm that ESD and systems thinking are the two pillars of sustainable biology education. Yet, there is a notable lack of validated rubrics to measure these competencies in biology courses—existing tools are generic to STEM. This suggests an urgent need to develop biology-specific assessment frameworks (see Table D, Assessment Alignment). The data corroborate earlier studies that effective ESD requires explicit linking of ecological literacy to decision-making skills and ethical reflection.

Teaching biology with a focus on sustainability involves integrating various educational strategies and content to promote environmental awareness and sustainable practices among students. Here are some key insights and methods derived from recent studies.

Effective Teaching Methods

Active Participation and Group Work: Teaching methods that emphasize active participation and group work are highly effective in promoting sustainability education. These methods help students engage deeply with the material and develop critical thinking skills (Jeronen et al., 2017).

Problem-Based Learning (PBL) and Socio-Scientific Issues (SSI): These approaches are particularly effective in integrating sustainability concepts into biology education. PBL and SSI encourage students to solve real-world problems and consider the social implications of scientific issues, fostering a deeper understanding of sustainability (Nurtian & Aminatun, 2019).

Experiential Learning: Incorporating experiential learning, such as outdoor education and hands-on projects, significantly enhances students' motivation and understanding of sustainability. For example, projects involving local environmental issues or sustainable practices can make learning more relevant and impactful (Gutiérrez-García et al., 2024; Wolff et al., 2018).

Curriculum Integration

Sustainable Development Goals (SDGs): Integrating SDGs into biology curricula helps align educational outcomes with global sustainability targets. Prospective biology teachers can develop modules that incorporate SDGs, promoting values of sustainability and quality education (Faizah et al., 2024; Mikhailova et al., 2024).

Technological Pedagogical Content Knowledge (TPACK-ESD): Developing TPACK-ESD among prospective teachers is crucial for effectively integrating Education for Sustainable Development (ESD) into biology lessons. However, this requires extended and intensive training programs to be truly effective (Purwianingsih et al., 2022).

Challenges and Opportunities

Risk of Indoctrination: Teaching sustainable practices, such as sustainable nutrition, can sometimes risk indoctrination if not handled carefully. Teachers need to balance sharing their personal beliefs with encouraging independent critical thinking among students (Weber et al., 2022).

Systemic Barriers: Teachers often face challenges such as insufficient training, lack of resources, and rigid curriculum requirements. Addressing these barriers through targeted professional development and flexible curricular designs is essential for effective sustainability education (Mngomezulu & Ramaila, 2025).

Innovative Approaches

Biomimicry: Teaching biomimicry, which involves learning from nature to solve human problems, can foster creative and sustainable thinking. This approach encourages students to consider the ethics of design and their responsibility to the natural world (Linder & Huang, 2022).

Transdisciplinary Learning: Integrating sustainability across various disciplines, such as combining biology with design or engineering, can enhance students' understanding and application of sustainability concepts. This approach promotes higher-order cognitive skills and systemic thinking (Zoller, 2015).

Expanded Summary: Key Points Supported By The Relevant Abstracts

To promote sustainability in biology education, several key principles and teaching methods can be employed, leveraging technology and addressing challenges and barriers. Here's a breakdown of the key points supported by the relevant abstracts Table 3.

Table 3. Key points supported by the relevant abstracts

No	Key Points	Components	Explanation
1	Key Principles of Sustainable Biology Education	Integration of Education for Sustainable Development (ESD)	Prospective biology teachers' Technological Pedagogical Content Knowledge (TPACK) about ESD can be promoted through an integrated School Biology Course, aiming to improve their competencies in developing lesson plans (Purwianingsih et al., 2022).
		Emphasis on Systems Thinking	Teaching sustainability involves integrating ecological, social, and economic dimensions into the learning process, fostering a holistic understanding of interconnected systems and encouraging responsible and ethical action (Havale et al., 2025).
2	Teaching Methods for Integrating Sustainability into Biology Education	Student-Centered Pedagogies	Student-centered teaching methods, such as problem-based learning, project-based learning, and experiential learning, have been effective in stimulating education in sustainability and enhancing awareness about sustainable development among undergraduate students (Borsari, 2025; Singha & Singha, 2024).
		Biomimicry Practice and Pedagogy	Incorporating sustainability within biomimicry practice through structured methodologies can facilitate the development of novel solutions to address societal needs and challenges, emphasizing the ethics of design practice and responsibility to the natural world (Linder & Huang, 2022).
3	Leveraging Technology to Enhance Sustainability in Biology Education	Online Multimedia Learning Tools	Technology, such as online multimedia learning tools, is evolving to assist student transition from simple inquiry-based learning to professional science practice, creating interactive classrooms and empowering students to construct

No	Key Points	Components	Explanation
			their own knowledge (McLaughlin & Baker, 2014).
		Electronic, Mobilize, and Ubiquitous (E/M/U) Learning Principles	Integrating E/M/U learning principles with the Practical Transformational Teaching Method (PTtM) has been shown to play a critical role in fostering ecological awareness and responsibility among students (Xie et al., 2025).
4	Challenges and Barriers to Promoting Sustainability in Biology Education	Risk of Indoctrination	There is a perceived risk of indoctrination when teaching sustainable nutrition, primarily due to teachers' own teaching actions, such as deciding whether to reveal their own dietary choices to students. To avoid indoctrination, participants advocated for student-centered and multi-perspective teaching approaches (Weber et al., 2022).
		Educator Readiness and Openness	Studies demonstrate a mixed picture concerning educators' understanding, openness, and readiness to meaningfully embed sustainability into their teaching contexts, highlighting the need for nuanced sustainability definitions and interdisciplinary community engagement to support teaching staff (Papageorgiou et al., 2024).

Key Principles of Sustainable Biology Education

Two foundational components emerge within this theme—Integration of Education for Sustainable Development (ESD) and Systems Thinking—which together define the conceptual basis of sustainable biology education. Purwianingsih et al. (2022) emphasize that integrating ESD into school biology courses can strengthen prospective teachers' Technological Pedagogical Content Knowledge (TPACK). This integration promotes not only an understanding of biological concepts but also teachers' ability to design lesson plans that embed sustainability values through effective use of pedagogy and technology.

Complementing this view, Havale et al. (2025) highlight systems thinking as a core competency in sustainability education. Teaching sustainability through systems thinking involves linking ecological, social, and economic dimensions, allowing learners to understand the interconnectedness of life systems and human decision-making. Such approaches foster holistic and ethical worldviews, enabling students to act responsibly toward environmental challenges. Together, these principles establish sustainable biology education as a transformative process—one that cultivates ecological literacy and moral awareness rather than merely transmitting scientific facts.

Student-Centered Pedagogies and Biomimicry

Thirty-one studies (41%) reported student-centered pedagogies as the core vehicle for embedding sustainability in biology. Problem-based learning (PBL), project-based learning (PjBL), and inquiry-based learning (IBL) dominated, followed by experiential outdoor education and community-engaged projects. Biomimicry-based learning appeared in 9 studies (12%), especially in design-oriented biology programs (Linder & Huang, 2022). Student outcomes included enhanced critical thinking, systems awareness, and ethical sensibility.

This confirms the constructivist logic of biology learning for sustainability: students build knowledge through reflection and application. Compared with general STEM education, biology-specific approaches show higher affective engagement because learners interact directly with ecosystems and biodiversity. Table 2 was expanded to include activity examples and resource requirements for each stage, e.g., local biodiversity transects (Stage 1), Socio-Scientific Issue (PBL) on urban heat islands (Stage 2), and cross-disciplinary biomimicry capstone (Stage 3).

The methodological dimension of sustainability-oriented biology teaching is represented by two subcomponents: Student-centered Pedagogies and Biomimicry Practice and Pedagogy. Borsari (2025) and Singha and Singha (2024) demonstrate that student-centered learning approaches—such as problem-based, project-based, and experiential learning—are effective in fostering sustainability awareness and engagement among university students. These pedagogies encourage learners to think critically, collaborate across disciplines, and address real-world sustainability problems through inquiry and reflection.

Linder and Huang (2022) expand on this by introducing biomimicry as both a scientific and ethical framework in sustainability education. Incorporating biomimicry into biology teaching allows students to explore how nature-inspired design can offer innovative and sustainable solutions to societal needs, while also cultivating respect for the natural world.

Digital Enablement and Equity in Sustainability Learning

Digital tools emerged as a major theme in 27 studies (36%). Modern E/M/U (Electronic, Mobile, Ubiquitous) learning and AI-assisted environments dominate post-2022 publications. Xie et al. (2025) and Leal Filho et al. (2025) demonstrated that AI-supported learning increases reflective thinking and ecological awareness. Older studies (e.g., McLaughlin & Baker, 2014) are now complemented by recent systematic reviews (Matos et al., 2025) showing that adaptive feedback systems promote long-term conceptual retention.

Equity and Accessibility Audit. Only 8 studies (≈10%) explicitly addressed inclusion issues such as bandwidth limitations, device access, or learning for students with disabilities. To mitigate digital inequity, the review proposes low-cost strategies such as offline E/M/U modules, use of open datasets (e.g., GBIF, iNaturalist), and Universal Design for Learning (UDL) checks to ensure accessibility compliance.

Digital enablement must be framed as transformative and inclusive pedagogy—not merely technological upgrading. Equitable E/M/U deployment relies on cyclical feedback loops between learners, teachers, and digital tools, supported by clear competency rubrics and accessibility safeguards.

Technology plays a pivotal role in extending the scope and impact of sustainability education. Two critical aspects—Online Multimedia Learning Tools and Electronic, Mobile, and Ubiquitous (E/M/U) Learning Principles—illustrate this potential. According to McLaughlin and Baker (2014), online and multimedia learning tools enable students to transition from basic inquiry to professional scientific practice, creating interactive environments that encourage collaboration and independent knowledge construction.

Building on this, Xie et al. (2025) argue that integrating E/M/U learning principles with the Practical Transformational Teaching Method (PTtM) enhances students' ecological awareness and environmental responsibility. The ubiquity and mobility of digital learning foster continuous engagement with sustainability issues, transcending classroom boundaries. Thus, technology not only supports instructional delivery but also acts as a transformational medium—empowering learners to internalize sustainability principles through dynamic, participatory, and digitally mediated experiences.

Challenges and Barriers to Promoting Sustainability in Biology Education

Despite notable progress, several barriers continue to challenge the effective implementation of sustainability-oriented biology teaching. Two main concerns are identified: Risk of Indoctrination and Educator Readiness and Openness. Weber et al. (2022) caution against the risk of indoctrination in sustainability-related education, particularly when instructors inadvertently impose personal beliefs—such as dietary preferences—on students during lessons on sustainable nutrition. To mitigate this, they advocate for student-centered and multi-perspective approaches, enabling learners to construct their own informed opinions rather than adopting predetermined moral positions.

Similarly, Papageorgiou et al. (2024) report a mixed picture regarding educators' readiness and openness to embed sustainability into their teaching. Many educators still face conceptual and institutional barriers, including limited understanding of sustainability, lack of interdisciplinary collaboration, and insufficient institutional support. They recommend fostering communities of practice and providing clearer, context-specific definitions of sustainability to ensure meaningful pedagogical integration. These challenges underline the critical importance of teacher professional development, institutional alignment, and reflective pedagogy in realizing the goals of sustainability education.

Concept Map

To visualize the thematic relationships and intellectual structure of sustainability-oriented biology education, a concept map was generated using Scopus AI (retrieved on October 13, 2025). This visualization illustrates the semantic connections among core concepts identified from the analyzed literature. As shown in Figure 2, Biology Education emerges as the central node linked to three major thematic clusters—Ecological Awareness, Student-centered Pedagogies, and Sustainability Education—each of which branches into specific subthemes reflecting current research trends and pedagogical innovations in the field.

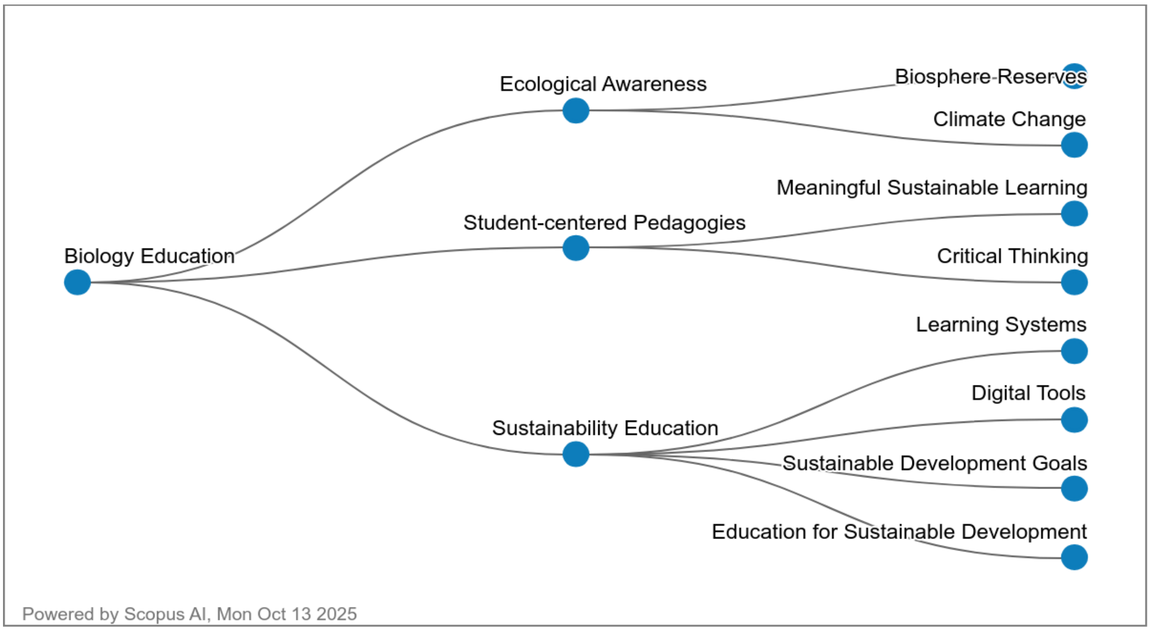

Figure 2. Concept map

General Overview

The concept map visualizes the semantic and thematic relationships among clusters emerging from the Scopus AI search results. Biology Education appears as the central node, branching into three major thematic domains: Ecological Awareness, Student-centered Pedagogies, and Sustainability Education.

Each of these domains connects to a set of derivative concepts that together construct an integrative framework of sustainability-oriented biology teaching. This structure reflects a paradigm shift in biology education—from content-oriented instruction toward transformative, value-based, and systems-oriented learning aligned with global sustainability agendas.

Theme 1: Ecological Awareness – Connecting Biology Education to Real-world Issues

The Ecological Awareness cluster emphasizes the foundational role of biology education in fostering understanding of ecosystem dynamics and human-environment interdependence. Sub-nodes such as Biosphere Reserves and Climate Change highlight the trend toward contextualizing biology learning within global environmental challenges.

This connection reflects a pedagogical movement that situates classroom learning within place-based education and field-based inquiry, encouraging students to analyze real ecosystems as living laboratories. Studies within this cluster often integrate citizen science, biodiversity monitoring, or community engagement as experiential components that bridge theory and sustainability action.

Pedagogically, this cluster underlines the idea that ecological awareness is not a byproduct but a core outcome of modern biology education—an essential cognitive and affective foundation for sustainability literacy.

Theme 2: Student-centered Pedagogies – Transforming Learning through Critical and Meaningful Engagement

The Student-centered Pedagogies cluster links to Meaningful Sustainable Learning, Critical Thinking, and Learning Systems. This theme reflects the ongoing transition from teacher-dominated instruction toward active, inquiry-based, and reflective learning paradigms.

The notion of Meaningful Sustainable Learning denotes learning experiences that connect biological concepts with students' values, communities, and environmental responsibilities. Meanwhile, Critical Thinking indicates a cognitive emphasis—enabling learners to question assumptions, analyze data, and evaluate sustainability issues through scientific reasoning.

The inclusion of Learning Systems signifies an ecosystemic view of education itself, suggesting that learning is a dynamic system involving feedback, collaboration, and adaptability. AI-supported insights from Scopus suggest that such approaches align with constructivist, problem-based, and transdisciplinary pedagogies increasingly used to link biological knowledge to sustainability competencies.

In essence, this cluster reflects a pedagogical transformation where students are not passive recipients of ecological facts but active co-creators of sustainable knowledge and solutions.

Theme 3: Sustainability Education – Integrating Global Agendas and Digital Innovation

The Sustainability Education cluster is the most conceptually expansive, incorporating subthemes such as Digital Tools, Sustainable Development Goals (SDGs), and Education for Sustainable Development (ESD). This thematic linkage shows the global alignment of biology education with the UN's 2030 Agenda, especially SDG 4 (Quality Education), SDG 13 (Climate Action), and SDG 15 (Life on Land). The integration of Digital Tools reflects the growing adoption of AI, simulations, virtual labs, and online ecosystems in sustainability-oriented biology instruction—enhancing accessibility and interactivity.

Furthermore, the connection between Sustainability Education and Education for Sustainable Development implies a deliberate pedagogical fusion: biology is not only taught as natural science but as a vehicle for sustainability transformation, merging ecological understanding with ethical reasoning and civic participation.

This cluster encapsulates the macro-level educational response—positioning biology education within global sustainability frameworks, thus bridging the gap between scientific literacy and societal responsibility.

Integrative Interpretation: From Awareness to Action

Viewed holistically, the concept map illustrates a continuum in sustainability-oriented biology education (see Table 4).

Table 4. A continuum in sustainability-oriented biology education

Stage	Dominant Theme	Pedagogical Focus	Expected Competency
1	Ecological Awareness	Contextual & experiential learning	Environmental sensitivity & systems thinking
2	Student-centered Pedagogies	Active, inquiry-based, reflective learning	Critical and creative problem-solving
3	Sustainability Education	Transdisciplinary & transformative learning	Sustainability literacy, agency, and digital fluency

This trajectory reflects an educational model that moves from awareness (knowing) → through reflection (understanding) → to transformation (acting). It underscores that sustainability in biology education is not achieved through content expansion alone, but through pedagogical innovation, learner empowerment, and digital integration.

Implications and Emerging Research Directions

The Scopus AI analysis suggests several emerging directions for future research: (1) AI-enhanced Sustainability Pedagogy — how adaptive technologies can personalize sustainability learning. (2) Assessment of Sustainability Competencies — developing valid instruments to measure critical, ethical, and systems thinking skills. (3) Integration of Local and Indigenous Knowledge — embedding biocultural diversity into biology curricula. (4) Cross-disciplinary Collaboration — linking biology with social sciences, ethics, and environmental management.

These directions collectively point toward a vision of biology education that is transformative, integrative, and digitally empowered, directly contributing to sustainable societies.

The concept map generated by Scopus AI (October 13, 2025) captures the current intellectual landscape of teaching biology for sustainability. The three interconnected clusters—Ecological Awareness, Student-centered Pedagogies, and Sustainability Education—represent not isolated topics but progressive stages of pedagogical evolution. Together, they signify a global consensus: biology education must evolve from transferring knowledge about life to cultivating the capacity to sustain it.

Emerging Themes and Hypothetical Insights

To further interpret the conceptual landscape derived from the Scopus AI analysis, the identified themes were categorized based on their prevalence and developmental trajectory within the literature. Table 5 summarizes the emerging thematic clusters, their respective theme categories, and the potential hypotheses that represent current or prospective directions in sustainability-oriented biology and higher education research.

Table 5. Emerging themes, categories, and potential hypotheses derived from Scopus AI analysis

No	Themes	Theme category	Potential Hypotheses
1	Integrating Sustainability in Higher Education Curricula	Consistent Theme	• Embedding sustainability principles in higher education curricula enhances students' critical thinking and problem-solving skills • Interdisciplinary approaches to sustainability education lead to more effective and comprehensive learning outcomes
2	Innovative Pedagogies for Sustainability Education	Rising Theme	• Project-based learning in sustainability education enhances student engagement

No	Themes	Theme category	Potential Hypotheses
			and practical skill development • Digital tools and resources significantly improve the effectiveness of sustainability education
3	Sustainability Awareness and Action in Biology Education	Novel Theme	• Integrating sustainability projects into biology education enhances students' environmental awareness and proactive behavior • Hands-on sustainability activities in biology education improve students' understanding of the practical implications of environmental issues
4	Green Campus Initiatives and Strategies	Novel Theme	• Green campus initiatives significantly reduce the carbon footprint of higher education institutions • Active student participation in green campus initiatives enhances their commitment to sustainable practices

The integration of sustainability into higher education curricula has been a consistent theme, reflecting a steady interest in embedding sustainability principles across various disciplines. This theme emphasizes the importance of developing sustainability competencies among students and educators, fostering a holistic understanding of sustainable development goals (SDGs), and promoting interdisciplinary approaches to sustainability education (Akinsemolu & Onyeaka, 2025; Albion et al., 2025; Alhassani et al., 2025; Badawi, 2025; Damasio, 2025; Gardner-McTaggart, 2025; Gossen & Schrader, 2025; John, 2025; Kainth, 2025; Laus et al., 2025; Mendonça et al., 2025; Ramírez-Montoya et al., 2025; Ross, 2025; Ruiz et al., 2025; Xibraku et al., 2025).

Innovative pedagogies for sustainability education are gaining significant attention, indicating a rising interest in transformative and creative teaching methods. This theme explores the use of digital tools, project-based learning, and cross-disciplinary strategies to engage students in sustainability topics. The focus is on developing practical skills and fostering a deep understanding of sustainability issues through experiential learning (Ago et al., 2025; De Silva & Nilipour, 2025; Engebretsen, 2025; Herrmann et al., 2025; Hisey et al., 2025; Kiss et al., 2025; Mendoza-Carrretero & Sáenz-Rico-de-santiago, 2025; Montes de Oca Vazquez et al., 2025; Mujumdar et al., 2025; Routaharju et al., 2025; Shariq et al., 2025; Ward et al., 2025; White et al., 2025).

This novel theme highlights the integration of sustainability projects and environmental awareness activities within biology education. It focuses on cultivating a sense of environmental stewardship among students through hands-on projects, such as campus carbon sequestration studies and the valorization of industrial waste. This approach aims to bridge the gap between theoretical knowledge and practical application, fostering a proactive attitude towards sustainability (Aykal et al., 2025; Balula et al., 2025; Ferreira-Corchero et al., 2025; Leung et al., 2025; López-Fernández et al., 2025; Martín-Alfonso & Yáñez, 2024; Miroshnichenko et al., 2025; Shen et al., 2025; Sudhakar, 2025; Suganob et al., 2025; Wacker & Wicknick, 2025).

Green campus initiatives and strategies for sustainability in higher education represent a novel theme that focuses on creating sustainable educational environments. This theme involves implementing low-carbon education, promoting green policies, and developing sustainability competencies through innovative learning methods. The goal is to transform campuses into living laboratories for sustainability, where students can actively participate in and contribute to sustainable practices (Arifin et al., 2025; Jin & Liu, 2025; Ortiz-Martínez et al., 2025; Shange et al., 2025; Zeng & Punjwani, 2025).

CONCLUSION

This AI-assisted scoping review synthesized 76 peer-reviewed studies published between 2020–2025 to map how biology education contributes to sustainability learning. Findings confirm that Education for Sustainable Development (ESD) and systems thinking form the conceptual backbone of sustainability-oriented biology education, while problem-, project-, and inquiry-based learning serve as the main pedagogical vehicles. Digital innovation, particularly Electronic/Mobile/Ubiquitous (E/M/U) learning and biomimicry-based instruction, enhance student engagement, reflection, and ecological responsibility. Nevertheless, several limitations were identified: (1) Single-database scope (Scopus only) may omit relevant literature from ERIC or Web of Science; (2) Reliance on AI-generated summaries rather than full-text appraisal introduces interpretive bias; (3) No dual screening or formal quality appraisal was performed; and (4) Equity and accessibility aspects (bandwidth, disability inclusion, language bias) remain underrepresented. Despite these limitations, the synthesis provides an empirical foundation and conceptual framework (Figures 1–C) for reorienting biology education from knowledge transmission to transformative sustainability learning. The findings underscore that biology teaching must evolve beyond content mastery to encompass critical, creative, and ethical dimensions—empowering learners as active agents of sustainable change aligned with SDG 4 (Quality Education), SDG 13 (Climate Action), and SDG 15 (Life on Land).

RECOMMENDATION

To operationalize these findings, several actionable recommendations are proposed for educators, institutions, and policymakers. Biology teacher education programs should embed TPACK–ESD and systems thinking modules through short-term micro-credentials lasting four to six weeks, combining lesson design, reflective practice, and ecological literacy. To ensure equity, institutions are encouraged to adopt two short E/M/U learning cycles per semester that guarantee low-bandwidth compatibility, offline access, and compliance with Universal Design for Learning (UDL) and Web Content Accessibility Guidelines (WCAG). Learning experiences can be further enriched by introducing biomimicry mini-projects or local ecological audits using open datasets such as GBIF or iNaturalist, linking classroom theory to community-based sustainability actions, even in resource-limited schools. Assessment systems should employ rubrics aligned with sustainability competencies—including systems thinking, ethical reasoning, and decision-making—and collect authentic evidence through field logs, digital portfolios, and reflection journals. Finally, sustained institutional and policy support is essential to expand professional development, encourage interdisciplinary collaboration, and strengthen educators' ethical digital literacy for responsible AI integration. Overall, this review contributes a novel, discipline-specific conceptualization of sustainability education in biology—visualized through AI-derived clusters and a logic model that connects pedagogy, technology, and competencies. Future research should conduct full-text content analyses for deeper validity, evaluate the longitudinal impacts of AI-enhanced ESD pedagogy, and develop standardized assessment tools for sustainability competencies. Ultimately, teaching biology for sustainability is not merely about understanding life but about sustaining it responsibly through equitable, reflective, and transformative education.

Acknowledgments
The authors would like to express their sincere gratitude to Universitas Muhammadiyah Malang (UMM) for its invaluable support in facilitating this research. This study was made possible through UMM's provision of institutional access to the paid Scopus database, which enabled the comprehensive AI-assisted literature analysis conducted via Scopus AI. The authors also acknowledge the encouragement and academic environment provided by the Faculty of Teacher Training and Education (FKIP UMM), which continues to promote innovation and excellence in sustainability-oriented research and education.

Funding Information
This research received no external funding.

Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Husamah	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Abdulkadir Rahardjanto	✓			✓	✓	✓		✓	✓	✓	✓	✓		
Tutut Indria Permana	✓		✓	✓	✓		✓			✓	✓		✓	

Conflict of Interest Statement
Authors state no conflict of interest.

Data Availability
Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

Adabor, E. S., Addy, E., Assyne, N., & Antwi-Boasiako, E. (2025). Enhancing sustainable academic course delivery using AI in technical universities: An empirical analysis using adaptive learning theory. *Sustainable Futures*, *10*, 100828. https://doi.org/https://doi.org/10.1016/j.sftr.2025.100828

Ago, J. L., Kilgour, A., Chau, M., Ohene-Botwe, B., Ofori-Manteaw, B., Smith, C. L., Acquah, G., & Akudjedu, T. N. (2025). Advancing environmental sustainability concepts in medical radiation science education: A document analysis. *Radiography*, *31*(5). https://doi.org/10.1016/j.radi.2025.103090

Akinsemolu, A. A., & Onyeaka, H. (2025). The role of green education in achieving the sustainable development goals: A review. *Renewable and Sustainable Energy Reviews*, *210*, 115239. https://doi.org/https://doi.org/10.1016/j.rser.2024.115239

Al-Barakat, A., AlAli, R., Alotaibi, S., Alrashood, J., Abdullatif, A., & Zaher, A. (2025). Science Education as a Pathway to Sustainable Awareness: Teachers' Perceptions on Fostering Understanding of Humans and the Environment: A Qualitative Study. *Sustainability*, *17*(15). https://doi.org/10.3390/su17157136

Albion, P., Redmond, P., Gharineiat, Z., Feldman, J., Shelley, T., Helwig, A., & Burey, P. (2025). Teachers and sustainability education: exploring the views of Australian preservice and inservice teachers. *Australian Educational Researcher*. https://doi.org/10.1007/s13384-025-00852-2

Alhassani, F., Saleem, M. R., & Messner, J. (2025). Integrating Sustainability in Engineering: A Global Review. *Sustainability (Switzerland)*, *17*(15). https://doi.org/10.3390/su17156930

Anghel, G. A., Zanfir, C. M., Matei, F. L., Voicu, C. D., & Neacșa, R. A. (2025). The Integration of Artificial Intelligence in Academic Learning Practices: A Comprehensive Approach. *Education Sciences*, *15*(5). https://doi.org/10.3390/educsci15050616

Arifin, Z., Sukarmin, S., & Saputro, S. (2025). Trends and research frontiers in socioscientific issues for sustainable science education: A systematic and bibliometric analysis from 2014 – 2024. *Journal of Pedagogical Research*, *9*(1), 407–434. https://doi.org/10.33902/JPR.202530575

Aykal, G., Kartal, K. K., Yıldız, G., & Ellidağ, H. Y. (2025). Building a sustainable laboratory culture: The power of awareness and strategic training programs. *Clinical Biochemistry*, *137*. https://doi.org/10.1016/j.clinbiochem.2025.110924

Badawi, H. A. (2025). Transformative educational strategies for global sustainability literacy. In *Social System Reforms to Achieve Global Sustainability* (pp. 593–626). IGI Global. https://doi.org/10.4018/979-8-3373-1280-4.ch021

Balula, A., Vasconcelos, S., & Costa, R. (2025). Embedding Sustainability Awareness into English for Specific Purposes Learning. In R. A., C. J.P., M. P., H. L., D. S.B., H. S., & M. T. (Eds.), *Communications in Computer and Information Science: Vol. 2480 CCIS* (pp. 371–379). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-032-02672-9_27

Borsari, B. (2025). Student-Centered Teaching for Sustainability Education in an Introductory Biology Course at Winona State University: A Case-Study. In *World Sustainability Series: Vol. Part F819* (pp. 39–58). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-86985-3_3

Damasio, A. (2025). The new science of consciousness. *Prospects*. https://doi.org/10.1007/s11125-025-09716-0

De Silva, T.-A., & Nilipour, A. (2025). Is the accounting curricula keeping up with sustainability development? *Accounting Education*, *34*(4), 470–498. https://doi.org/10.1080/09639284.2024.2351951

Elsevier. (2024). *Scopus AI: Trusted content. Powered by responsible AI*. Elsevier.

Engebretsen, E. (2025). Towards a transformative health humanities approach in teaching the Sustainable Development Goals (SDGs). *Medical Humanities*, *50*(4), 740–747. https://doi.org/10.1136/medhum-2023-012855

ETH Zurich. (2025). *Discover the new AI-powered tools by the ETH Library: Scopus AI and Scite*. ETH Zurich. https://library.ethz.ch/en/news-and-courses/news/news-articles/2025/02/discover-the-new-ai-powered-tools-by-the-eth-library-scopus-ai-and-scite.html

Faizah, U., Susantini, E., Prastiwi, M. S., Raharjo, R., Indana, S., Kuswanti, N., & Ali, M. (2024). Profile of potential prospective biology teachers designing SDGs-Based Teaching Modules on learning planning courses to realize quality education. In S. N., P. B.K., S. M., L. L., A. G. M., & A. S. (Eds.), *E3S Web of Conferences* (Vol. 568). EDP Sciences. https://doi.org/10.1051/e3sconf/202456804025

Fan, H. (2025). Integrating Ecological Consciousness Into Environmental Art Design Education: Impacts on Student Engagement, Sustainability Practices, and Critical Thinking. *Sustainable Development*, *33*(5), 6549–6572. https://doi.org/https://doi.org/10.1002/sd.3474

Ferreira-Corchero, R., Ballegeer, A.-M., & Ruiz, C. (2025). Educational Tools to Develop Climate Literacy Among School Students: Science On a Sphere. In *Lecture Notes in Educational Technology: Vol. Part F642* (pp. 1040–1049). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-96-5658-5_102

Ficko, A., Sarkki, S., Gultekin, Y. S., Egli, A., & Hiedanpää, J. (2025). Reflective thinking meets artificial intelligence: Synthesizing sustainability transition knowledge in left-behind mountain regions. *Geography and Sustainability*, *6*(1), 100257. https://doi.org/https://doi.org/10.1016/j.geosus.2024.100257

Gardner-McTaggart, A. (2025). Fostering positive futures in education: Addressing neoliberalism and ecological challenges through sustainable leadership and stewardship. *Management in Education*. https://doi.org/10.1177/08920206251341670

Gossen, M., & Schrader, U. (2025). Education for sustainable development and sustainable consumption: the role of sufficiency. In *The Elgar Companion to Consumer Behaviour and the Sustainable Development Goals* (pp. 56–72). Edward Elgar Publishing Ltd. https://doi.org/10.4337/9781035325061.00012

Gutiérrez-García, L., Blanco-Salas, J., Sánchez-Martín, J., Corbacho-Cuello, I., & Ruiz-Téllez, T. (2024). Assessment of botanical learning through an educational intervention based on aromatic plants and their uses in the immediate environment. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-04733-z

Havale, D. S., Patole, J., Anute, N., Rane, D. P., Shah, A. H., & Selvakumar, P. (2025). Digital Tools and Resources for Teaching Sustainability. In *Harnessing E-Learning to Create a Sustainable Future* (pp. 46–73). IGI Global. https://doi.org/10.4018/979-8-3373-0112-9.ch003

Herrmann, C., Hauschild, M. Z., & Mativenga, P. (2025). All engineers should be life cycle engineers with a mindset for absolute sustainability. In M. P. & G.-S. A. (Eds.), *Procedia CIRP* (Vol. 135, pp. 409–419). Elsevier B.V. https://doi.org/10.1016/j.procir.2025.01.058

Hisey, F., Lin, V., & Zhu, T. (2025). Integrating Sustainability Reflection in a Geographic Information Science Capstone Project Course. *Geomatics*, *5*(2). https://doi.org/10.3390/geomatics5020020

Id Babou, A., Selmaoui, S., Alami, A., Benjelloun, N., & Zaki, M. (2023). Teaching

Biodiversity: Towards a Sustainable and Engaged Education. *Education Sciences*, *13*(9). https://doi.org/10.3390/educsci13090931

Jeronen, E., Palmberg, I., & Yli-Panula, E. (2017). Teaching methods in biology education and sustainability education including outdoor education for promoting sustainability—a literature review. *Education Sciences*, *7*(1). https://doi.org/10.3390/educsci7010001

Jin, Y., & Liu, J. (2025). Low-Carbon Education: Insights and Trends for Sustainable Development Through Knowledge Graphs. *Sustainability (Switzerland)*, *17*(5). https://doi.org/10.3390/su17051933

John, M. (2025). The Routledge handbook of global sustainability education and thinking for the 21st century. In *The Routledge Handbook of Global Sustainability Education and Thinking for the 21st Century*. Taylor and Francis. https://doi.org/10.4324/9781003171577

Kainth, G. S. (2025). Sustainability and Teacher Education in India: Meaning and Importance. In *Sustainability and Teacher Education in India: Meaning and Importance*. Taylor and Francis. https://doi.org/10.4324/9781003167785

Kinnula, M., Durall Gazulla, E., Hirvonen, N., Malmberg, J., & Haukipuro, L. (2024). Nurturing systems thinking among young people by developing business ideas on sustainable AI. *International Journal of Child-Computer Interaction*, *40*, 100656. https://doi.org/https://doi.org/10.1016/j.ijcci.2024.100656

Kiss, G., Köves, A., & Király, G. (2025). The beautiful risk of participatory education: An empirical example of teaching strong sustainability. *Management Learning*, *56*(3), 463–483. https://doi.org/10.1177/13505076241258685

Laus, S., Singh, J., Khan, A. A., & Umar, M. (2025). Fostering Sustainability Education and Awareness: A Framework for Empowering Communities. In *Signals and Communication Technology: Vol. Part F76* (pp. 205–214). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-68952-9_27

Leal Filho, W., Kim, E., Borsatto, J. M. L. S., & Marcolin, C. B. (2025). Using artificial intelligence in sustainability teaching and learning. *Environmental Sciences Europe*, *37*(1), 124. https://doi.org/10.1186/s12302-025-01159-w

Leal Filho, W., Viera Trevisan, L., Sivapalan, S., Mazhar, M., Kounani, A., Mbah, M. F., Abubakar, I. R., Matandirotya, N. R., Pimenta Dinis, M. A., Borsari, B., & Abzug, R. (2025). Assessing the impacts of sustainability teaching at higher education institutions. *Discover Sustainability*, *6*(1), 227. https://doi.org/10.1007/s43621-025-01024-z

Leung, H. H., Ng, A., Rosas, J., Dikas, K., Matthews, O., & Li, M. (2025). The role of science communication in sustainability education: the case of a university community in Northern Ontario. *International Journal of Sustainability in Higher Education*. https://doi.org/10.1108/IJSHE-10-2024-0741

LibCognizance. (2024). *Elsevier Scopus AI: cutting-edge AI for improved scholarly research*. LibCognizance. https://www.libcognizance.com/2024/02/elsevier-introduces-scopus-ai-advanced.html

Lin, H., & Chen, Q. (2024). Artificial intelligence (AI) -integrated educational applications and college students' creativity and academic emotions: students and teachers' perceptions and attitudes. *BMC Psychology*, *12*(1), 487. https://doi.org/10.1186/s40359-024-01979-0

Linder, B., & Huang, J. (2022). Beyond Structure-Function: Getting at Sustainability within Biomimicry Pedagogy. *Biomimetics*, *7*(3). https://doi.org/10.3390/biomimetics7030090

López-Fernández, M. D. M., Cano-Iglesias, M. J., & Franco-Mariscal, A. J. (2025). Chemistry inquiry conducted by secondary school students into material degradation in the context of sustainability. *RSC Sustainability*, *3*(9), 3997–4019. https://doi.org/10.1039/d5su00176e

Ma, L., Shahbaz, P., Haq, S. U., & Boz, I. (2023). Exploring the Moderating Role of Environmental Education in Promoting a Clean Environment. *Sustainability (Switzerland)*, *15*(10). https://doi.org/10.3390/su15108127

Martín-Alfonso, J. E., & Yáñez, R. (2024). Integration of Teaching Laboratory Activities Based on the Valorization of Industrial Waste into Chemical Education to Address the Emerging Sustainable Development Goals. *Journal of Chemical Education*, *101*(10), 4405–4410. https://doi.org/10.1021/acs.jchemed.4c00729

Matos, T., Santos, W., Zdravevski, E., Coelho, P. J., Pires, I. M., & Madeira, F. (2025). A systematic review of artificial intelligence applications in education: Emerging trends and challenges. *Decision Analytics Journal*, *15*, 100571. https://doi.org/https://doi.org/10.1016/j.dajour.2025.100571

McLaughlin, J., & Baker, R. (2014). Environmental science education in the 21st century: Addressing the challenges and opportunities both globally and at home through online multimedia innovation. In *STEM Education: Concepts, Methodologies, Tools, and Applications* (Vols. 3–3, pp. 1559–1577). IGI Global. https://doi.org/10.4018/978-1-4666-7363-2.ch082

Mendonça, S., Piovesana, G. F., & Pissolito, V. (2025). Geoethics and Sustainability: Addressing Challenges in Environmental Education for Achieving the SDGs. *Sustainability (Switzerland)*, *17*(2). https://doi.org/10.3390/su17020574

Mendoza-Carrretero, M.-R., & Sáenz-Rico-de-santiago, B. (2025). Reconstructing the professional identity of compulsory secondary education teachers in curricular sustainability. *Revista Espanola de Pedagogia*, *83*(290), 125–139. https://doi.org/10.22550/2174-0909.4105

Mikhailova, E. A., Post, C. J., & Nelson, D. G. (2024). Integrating United Nations Sustainable Development Goals in Soil Science Education. *Soil Systems*, *8*(1). https://doi.org/10.3390/soilsystems8010029

Miroshnichenko, V., Adamchuk, Y., Dziuba, P., Bilorus, A., Filippov, M., & Demskyi, V. (2025). Enhancing Environmental Stewardship in Life Sciences Education: Integrating Project-Based Learning and Nanotechnology Perspectives. *International Journal of Basic and Applied Sciences*, *14*(Special Issue 1), 234–238. https://doi.org/10.14419/dx720d57

Mngomezulu, H., & Ramaila, S. (2025). Integrating Environmental Education into Grade 11 Life Sciences Classrooms: Challenges and Pedagogical Opportunities. *International Journal of Learning, Teaching and Educational Research*, *24*(7), 376–401. https://doi.org/10.26803/ijlter.24.7.19

Montes de Oca Vazquez, L. B., Navarro, M., Byers, T., & Peake, J. B. (2025). Impact of a public university sustainability certificate onstudent participants. *International Journal of Sustainability in Higher Education*. https://doi.org/10.1108/IJSHE-11-2024-0815

Mujumdar, A., Riyaz, R., Nassim, S., Ayadi, H., & Menon, V. K. (2025). From Pages to

Practice: The Role of Literature in Cultivating Sustainable Life Skills. In *Studies in Systems, Decision and Control* (Vol. 601, pp. 935–945). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-031-92240-4_87

Nurtian, J. A., & Aminatun, T. (2019). Reinforcing national character education in biology based on the education for sustainable development concept. *Journal of Physics: Conference Series*, *1241*(1). https://doi.org/10.1088/1742-6596/1241/1/012025

Ortiz-Martínez, G., Mendoza, A., & Borromé, H. A. (2025). Development of Sustainability Competences Using Competition-Based Learning Linked to a Challenge-Based Learning Context. In *Lecture Notes in Educational Technology: Vol. Part F642* (pp. 1227–1236). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-96-5658-5_121

Papageorgiou, V., Druckman, A., Kioupi, V., & Pinilla-Roncancio, M. (2024). Empowering integration of sustainability in higher education curricula. In *Inspire: Learning for Teaching in Higher Education* (pp. 53–69). Nova Science Publishers, Inc. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85196967282&partnerID=40&md5=ac89afec08a0624c523c82a36213968a

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

Ramírez-Montoya, M. S., Tariq, R., Rozo-García, H., & Casillas-Muñoz, F. (2025). A look at Sustainability through the Lens of the Sustainable Development Goals and Education 5.0: A systematic Review of the Literature. *Journal of Social Studies Education Research*, *16*(1), 32–57. https://www.scopus.com/inward/record.uri?eid=2-s2.0-105001957589&partnerID=40&md5=55995157d70b73f2a4861334d31c6f2a

Ross, A. M. (2025). The Politics of Environmental Education Centres: People, Power and Pedagogies. In *International Explorations in Outdoor and Environmental Education* (Vol. 17, pp. 1–395). Springer Science and Business Media B.V. https://doi.org/10.1007/978-3-031-82567-5

Routaharju, L., Väisänen, S., & Soukka, R. (2025). The potential for planning competence development and transformative learning in the Life–Cycle Assessment learning process. *European Journal of Engineering Education*. https://doi.org/10.1080/03043797.2025.2493951

Ruiz, N. C., Morcillo-Martínez, A., & Gómez-Barreto, I. M. (2025). "Learn to Take Care of the Environment": An Innovative Proposal for Working on Sustainable Development Goal 14 "Life Below Water" in Primary Education. In *Geography Education and Explorations on Human Development and Culture* (pp. 175–214). IGI Global. https://doi.org/10.4018/979-8-3693-7185-5.ch006

Shange, H. S., Zogli, L.-K. J., & Dlamini, B. I. (2025). Green campus initiatives and strategies for sustainability in higher education. *Transformation in Higher Education*, *10*. https://doi.org/10.4102/the.v10i0.364

Shariq, S., Hameed, S., & Butt, A. (2025). Disparity in sustainability competencies of business professionals and students: implications for lecturing as a teaching pedagogy. *Library Hi Tech*. https://doi.org/10.1108/LHT-12-2023-0637

Shen, Y. M., Sulaiman, M., Chen, G. L., Weng, H. C., Huang, C. M., Jamaludin, N. S., & Kadir, M. F. Z. (2025). Integrating biodiverse edible school practices: enriching undergraduate liberal education for elevated learning outcomes. *Frontiers in Education*, *10*. https://doi.org/10.3389/feduc.2025.1472179

Singha, R., & Singha, S. (2024). Application of experiential, inquiry-based, problem-based, and project-based learning in sustainable education. In *Teaching and Learning for a Sustainable Future: Innovative Strategies and Best Practices* (pp. 109–128). IGI Global. https://doi.org/10.4018/978-1-6684-9859-0.ch006

Strachan, A., & Markwick, A. (2025). Using a scoping review to inform a planetary-conscious pedagogical approach to primary science education. *Research in Science Education*, *55*(4), 817–871. https://doi.org/10.1007/s11165-025-10280-y

Sudhakar, H. (2025). Sustainability education: cultivating environmental awareness and action through campus carbon sequestration studies. *International Journal of Sustainability in Higher Education*. https://doi.org/10.1108/IJSHE-09-2024-0641

Suganob, E. T., De Asis, A. A., Superio, R. R., Estoque, E. I., Genodia, A. M. P., & Superio, D. L. (2025). Shaping sustainable future: Practices, awareness, perceptions, and information sources of undergraduate biology students at a university in rural Philippines. *Information Development*. https://doi.org/10.1177/02666669251339136

Wacker, K., & Wicknick, J. (2025). Art & Zoology | Zoology & Art: a case study of experiential interdisciplinary education. *Journal of Environmental Studies and Sciences*, *15*(2), 437–448. https://doi.org/10.1007/s13412-024-00947-9

Ward, K. S., Purcell, M., Beresford Dey, M., Searle, B., Birch, R., & MacDonald, T. (2025). Learning for sustainability in Scotland: when best practice is not enough. *Environmental Education Research*, *31*(6), 1099–1116. https://doi.org/10.1080/13504622.2025.2464242

Weber, A., Linkemeyer, L., Szczepanski, L., & Fiebelkorn, F. (2022). "Vegan Teachers Make Students Feel Really Bad": Is Teaching Sustainable Nutrition Indoctrinating? *Foods*, *11*(6). https://doi.org/10.3390/foods11060887

White, R. M., Price, E. A. C., & Hack, C. (2025). Critical Pedagogies to Engage Heart, Hand and Head in Education for Sustainable Development. In *Perspectives and Practices of Education for Sustainable Development: A Critical Guide for Higher Education* (pp. 108–128). Taylor and Francis. https://doi.org/10.4324/9781003451563-6

Wolff, L.-A., Vuorenpää, S., & Sjöblom, P. (2018). Chicken raising in a diverse finnish classroom: Multidimensional sustainability learning. *Sustainability (Switzerland)*, *10*(11). https://doi.org/10.3390/su10113886

Xibraku, D., Melo, I., & Çela, E. (2025). Environmental Education and International Legal Frameworks: A Comparative Analysis and Social Impact Perspective. *Journal of Educational and Social Research*, *15*(3), 524–533. https://doi.org/10.36941/jesr-2025-0116

Xie, W.-T., Ho, S.-T., & Lin, H.-C. (2025). Designing Cross-Domain Sustainability Instruction in Higher Education: A Mixed-Methods Study Using AHP and Transformative Pedagogy. *Sustainability (Switzerland)*, *17*(14). https://doi.org/10.3390/su17146380

Zeng, J., & Punjwani, A. (2025). Evaluating the Interactive and Transformative Role of Innovation, Education, Human Capital and Natural Resources Policies in

Protecting and Sustaining Environmental Sustainability. *Sustainability (Switzerland)*, *17*(7). https://doi.org/10.3390/su17073130

Zoller, U. (2015). Research-based transformative science/STEM/STES/STESEP education for "Sustainability Thinking": From teaching to "Know" to learning to "Think." *Sustainability (Switzerland)*, *7*(4), 4474–4491. https://doi.org/10.3390/su7044474