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Bibliometric and Content Analysis of Sustainable Education in Biology for Promoting Sustainability at Primary and Secondary Schools and in Teacher Education

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Abstract

The integration of sustainable development into biology education has been a growing area of interest. Biology education for sustainability is considered through competencies and skills, taking different dimensions of knowledge into account. Solving problems requires not only knowledge but also communicative and strategic activity. Thus, biology education must emphasize the main visions of scientific literacy proposed in the literature, supporting students to understand society and everyday socioscientific challenges at the local as well as at the global level, and to deal with differing scientific results and uncertain information. However, there are very few studies from a holistic didactic viewpoint on the implementation of sustainable education (SE) in biology education in the context of teacher education and school education for promoting a sustainable future. This study addresses this gap via a bibliometric and content analysis of the literature (n = 165 and 131, respectively) based on the categories of the sustainable development goals (SDGs), subject aims, learning objectives, content knowledge, teaching methods, competencies and skills, and assessment methods. The literature analyzed emphasizes the environmental and social SDGs, the development of students' factual and conceptual knowledge and learning, interactive teaching and learning methods, critical thinking and reflection, and summative and formative assessment methods. There is much less attention on economic and institutional SDGs, scientific skills, environmental attitudes, knowledge creation, strategic thinking and empathy, and diagnostic assessment methods. Compared to earlier studies performed in the 2010s, teaching and learning methods have become more diverse in contrast to the earlier focus on teacher-centered methods. Overall, the conclusion is 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 quality education (SDG 4), good health and well-being (SDG 3), and life on land (SDG 15). The findings also suggest that powerful knowledge needs to be emphasized for providing essential insights into ecosystems, biodiversity, and the processes that sustain life on Earth. They also highlight the importance of regular evaluations of teaching and learning for detecting how pedagogical and didactic approaches and strategies have supported students' learning focused on sustainable development.

Keywords: biology education; sustainability; sustainable development goals (SDGs); sustainable education (SE); teacher education; school teaching; transformative teaching and learning; sustainability competencies and skills; scientific literacy

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1. Introduction

For promoting sustainable development locally, regionally, and globally, the United Nations published the document named 'Transforming Our World: The 2030 Agenda for Sustainable Development' (called Agenda 2030) in 2021 (UN, 2021). At its core are 17 SDGs, which are grouped into environmental, social, economic, and institutional dimensions (UN, 2021). All the SDGs are both interrelated and interdependent. Agenda 2030 and its 17 SDGs are focused both on the environment and a multidimensional approach to sustainable development to achieve the well-being of people around the world (Di Fabio, 2017).

Sustainable development depends on the ability and willingness of humans to shift their behavior toward maintaining ecological integrity in human relationships with Earth. Education has a good chance of influencing this shift when teaching and learning are developed according to action-oriented transformative education, which is characterized by "people-nature interdependence, future focus, common agendas for sustainability and personal and societal behavior regarding production and consumption" (Fricke et al., 2015, p. 17). Howlett et al. (2016) have pointed out that educators, as important change agents, need to rethink the learning process to enhance students' understanding of the drastic consequences for human life resulting from the overexploitation of a planet with finite resources.

The necessary cultural change can be achieved through sustainable education (SE). SE refers to finding sustainable solutions to environmental, social, and economic problems through education (Prabakaran, 2020). It challenges education to actively participate in the creation of environmental, social, and economic programs that improve quality of life, increase empowerment, and respect interdependence (Abduganiev & Abdurakhmanov, 2020). The skills needed for a sustainable development breakthrough can be promoted, for example, through transformative teaching and learning (Odell et al., 2019), where the focus is on critical reflection on knowledge in relation to the student's own worldview and preconceptions (Aboytes & Barth, 2020). This requires the development of student participation, agency, and pedagogical solutions, as well as a commitment to sustainable development practices and sustainable education in teaching and learning activities.

Biology education plays an important role in promoting sustainable development by integrating a variety of educational strategies and subject content that promote understanding of sustainable development practices, environmental stewardship (Akinwumi, 2023), and also, for example, solving questions about food, transport, climate change, and threats to health in a sustainable way.

The integration of sustainable development into biology education is a growing area of interest. Lozano et al. (2017) have sought to link pedagogical approaches to sustainability competencies. Vare et al. (2019) have explored the competencies that might underpin a qualification in education relating to sustainable development in any context. However, the application of didactic theories to practical teaching and learning processes has remained limited (Vare et al., 2019). The key gaps identified are the integration of sustainable development in curricula (Avelar et al., 2023) as well as in teaching methods and pedagogical approaches. There are also many previous studies focusing on, e.g., students' conceptions of subject content (Brechet et al., 2022; Palmberg et al., 2016, 2018; Sá-Pinto et al., 2022; Yli-Panula et al., 2017a, 2017b) and teaching methods in biology education (Biggers, 2018; Faruhana et al., 2022; Hafeez, 2021; Kassa et al., 2024).

To the best of our knowledge, although a significant amount of research on SE and biology education has been published, there are very few studies from a holistic didactic viewpoint on the implementation of SE in biology education in the context of teacher education and school education for promoting a sustainable future. In order to fill this gap, this paper aims (1) to clarify the state of the art in the domain and (2) to use the insights of this literature review to propose ideas for integrating SE with biology education. In

doing so, it contributes to a deeper understanding of holistic biology education related to sustainable development to shape the development of curricula and teaching practices in biology education in teacher education and at primary and secondary schools.

2. Theoretical Background

Successful teaching of biology requires the ability to think concretely, abstractly, and critically. Perceptions on biology and its teaching have changed over the decades. This section first presents visions of scientific literacy and sustainable development goals. Thereafter, the role of biology education promoting sustainable development is described as approaches and methods of teaching play a central role in promoting sustainable development (EC, 2022; Uitto & Saloranta, 2017).

2.1. Visions of Scientific Literacy

Biology in the 21st century requires a revolution in teaching that corresponds to the revolution that the discipline experienced in the final decades of the 20th century. Science education, including biology education, has expanded from traditional subject-specific emphases to the individual, societal, and professional significance of knowledge and skills for students in their own lives. Many biologists think that, in education, new instructional approaches and practices need to be implemented.

Researchers have developed various visions and frameworks to structure and implement these changes in science education. For example, Roberts (2007) distinguishes the mastery of scientific content and methods (Vision I) and how science relates to the real world in different social contexts (Vision II). Vision I focuses on the processes and results of science and seeks to educate individuals who can effectively utilize scientific tools and facts. Vision II, by contrast, embraces the sociocultural applications of science and embeds science in society, culture, and personal experiences. Sjöström and Eilks (2018) expand on this, defining three visions for science education, in which the significance and emphasis of knowledge and skills are different. Interpreting the studies of Roberts (2007) and Sjöström and Eilks (2018), in addition to the basic goals of science education (Vision I, "science literacy", cf. ecological literacy), the current emphasis is on the application skills and usability of scientific knowledge and skills in terms of the student's own life decisions, also outside of school (Vision II, "scientific literacy", cf. environmental literacy). Sjöström and Eilks' Vision III ("science for transformation") focuses beyond the field of knowledge, from the individual to society (cf. ecoliteracy). Education aims to foster critical, socially aware, and participating citizens who are able to apply biological knowledge and skills to complex sustainability challenges (Uitto et al., 2024a).

The central idea of science education, including biology education, is creating a foundation for the student's scientific literacy (Roberts, 2007). In teacher education and in school education, the development of scientific literacy involves three areas of scientific content knowledge (cf. OECD, 2019):

1. *Subject content knowledge*: knowledge of the content of biology, such as phenomena from molecules to the biosphere.
2. *Procedural knowledge*: knowledge of the methods of obtaining information in biological research that are needed to produce reliable and testable information.
3. *Epistemic knowledge*: knowledge of biology as a natural science, its procedures for studying and explaining phenomena in the natural world, and ways to test and argue for information critically on the basis of research-based evidence using models and other scientific methods of presentation.

Vision I includes students' inquiry skills (Siarova et al., 2019), and Vision II and Vision III emphasize relevance (Valladares, 2021). The difference is that Vision II highlights

everyday life relevance, while Vision III emphasizes the relevance for critical citizenship and sustainability (Sjöström & Eilks, 2018). Even though the three visions of scientific literacy are dissimilar in content and purpose, they depend on and enhance each other and overlap to some extent. According to the visions, the core subject aims in school science, including biology education, are that students learn to critically examine their own assumptions and beliefs, to take emotions into account, and to be aware of and understand contradictions. They should learn negotiation, problem-solving, and decision-making skills through discussions about ecological, social, economic, and ethical principles concerning local and global responsibility in their own life.

2.2. Sustainable Development Goals (SDGs) and Educational Approaches Promoting Sustainable Development

An ongoing debate over the last three decades has been how the role of education should be conceptualized when creating sustainability and a sustainable future. Recently, the 2030 Agenda proposed a focus on the role of education in achieving sustainable development (UN, 2021). It covers the four main dimensions (environmental, social, economic, and institutional) of sustainable development (UN, 2021).

The *environmental dimension* includes SDG 6 [clean water and sanitation], SDG 7 [affordable and clean energy], SDG 12 [responsible consumption and production], SDG 13 [climate action], SDG 14 [life below water], and SDG 15 [life on land]. The *social dimension* consists of SDG 1 [no poverty], SDG 2 [zero hunger], SDG 3 [good health and well-being], SDG 4 [quality education], SDG 5 [gender equality], and SDG 10 [reduced inequalities]. The economic and institutional dimensions each contain only a couple of SDGs. The *economic dimension* has SDG 8 [decent work and economic growth], SDG 9 [industry, innovation, and infrastructure], and SDG 11 [sustainable cities and communities]. Finally, the *institutional dimension* contains SDG 16 [peace, justice, and strong institutions] and SDG 17 [partnerships for the goals] (UN, 2021).

SDG 4, called "quality education", particularly focuses on ensuring inclusive and equitable quality education and to promote lifelong learning opportunities for all (UNESCO, 2017a). "Quality education" is a specific goal that directly impacts the other goals. Its role is also crucial in sustainability. The characteristics of quality education in relation to sustainable development are presented in Table 1.

Table 1. Main and sub-characteristics of quality education in relation to sustainable development (Efe & Umdu Topsakal, 2025).

Main Characteristics	Sub-Characteristics
Comprehensive and practical	Interdisciplinary Holistic Applicable
Value- and skill-focused	Critical and creative thinking Adopting norms and principles Acquiring 21st century skills
Collaborative and participatory	Teamwork with awareness of social sustainability Ability to cooperate socially

Quality education enables action, for example, on the following SDGs: "decent work and economic growth", "industry, innovation, and infrastructure", and "sustainable cities and communities". It also promotes individuals' sustainable mindsets and values and supports behavioral change towards sustainable development. It enables individuals

to take responsibility for their decisions and actions and to be aware of their impact on sustainability (Espinosa-Gutirrez et al., 2025).

The educational approaches promoting sustainable development reflect the change in emphasis over time. Their aims and contents have different emphases. For example, the concepts "education for sustainable development", "sustainability education", and "sustainable education" differ in that the first one emphasizes the need for change in individual behavior, while the latter two emphasize the need for change in local, national, and international organizational culture (Sterling et al., 2018). However, all three approaches can be understood to integrate the dimensions of sustainable development and to share a common vision of quality education and a society that lives in balance with the carrying capacity of Earth. They include inter- and multidisciplinary views, societal issues at the local, regional, and global levels, as well as changes in education.

This study examines the teaching of sustainable development in biology education from the viewpoint of sustainable education (SE). Sterling (2001, p. 22) defines SE as

> a change of educational culture, one which develops and embodies the theory and practice of sustainability in a way which is critically aware. It is therefore a transformative paradigm which values, sustains and realises human potential in relation to the need to attain and sustain social, economic and ecological well being, recognising that they must be part of the same dynamic.

The integration of SE into biology education is a practical way to support students' understanding of sustainable development and to foster transformative sustainable action.

The educational development of future educators can be characterized as a journey that should be based on Agenda 2030 and its SDGs (Avelar et al., 2023). However, there have been differing views on how this sustainable development teaching and learning should be implemented, experienced, and assessed in teacher education and at schools (Dyllick, 2015). This study aims to gain information on how the SDGs and sustainable development have been implemented in biology education to date.

2.3. Biology Education Promoting Sustainable Development

Sustainable development today is a part of the European basic education and upper secondary education, and it should be included in the curricula of different subjects, e.g., natural sciences (EC, 2024), including biology. This means that the teaching of subjects and subject education plays an important role in SE at schools. Different subjects have their own strengths in teaching sustainable development ideas (Uitto & Saloranta, 2017), and in teaching ideas that cross subject boundaries (cross-subject didactics, Sjöström et al., 2024), due to the fact that the subject aims and learning objectives, topics, teaching methods, and also evaluation and assessment methods differ across different subjects. Thus, the nature of the subject (Gericke, 2022; Uitto & Saloranta, 2017) influences how sustainable development and its ecological, social, and economic dimensions are taught in school and teacher education.

Biology education is closely linked to SE. Such links exist, e.g., in the fields of ecology, biodiversity, conservation, and system biology. Biological phenomena connected to socioscientific issues, such as climate change, need to have an integrative and interdisciplinary approach to be thoroughly taught and learned. In this section, competencies and skills, subject aims and learning objectives, knowledge types, teaching and learning methods, and evaluation and assessment methods in biology education promoting sustainable development are discussed.

2.3.1. Competence Frameworks, Competencies, and Skills

In competence frameworks, subjects such as biology do not have a separately stated significance, but the objectives are described as being linked to all educational levels. In addition to the UNESCO (2017b) competence framework, the European Union has

developed its own GreenComp competence framework (Bianchi et al., 2022). Competence frameworks can be used to promote SE in universities and colleges, teacher education, and vocational education.

The descriptions of competencies for sustainable development in UNESCO (2017b) and in GreenComp (Bianchi et al., 2022) are similar, but there are also differences. Both descriptions include the goals of valuing sustainable development, supporting equity, as well as individual and community agency to promote sustainability. Both documents are aimed at educators and policymakers, but UNESCO focuses specifically on curriculum development, whereas GreenComp also has employers as a key target group. In addition to improving workplace practices, GreenComp emphasizes political agency and readiness to respond to the demands of a green economy (Sourgiadaki & Karkalakos, 2023). This study examines SE in biology education based on UNESCO (2017b).

Competencies mean the ability to understand the interdependencies of ecological, social, and economic systems (UNESCO, 2017b), and they are connected to skills. Skills are the ability and capacity to carry out processes and use one's existing knowledge to achieve results (EU, 2018). In this study, key competencies are understood as distinct definable competencies concerning different areas of sustainability knowledge (Table 2, UNESCO, 2017b). They are transversal, context-independent, multidisciplinary, and relevant to all SDGs. They have been considered necessary for students of all ages around the world. Key competencies enable persons to relate the different SDGs to each other—to see "the big picture" of the 2030 Agenda for Sustainable Development (UN, 2021).

Table 2. Key competencies (UNESCO, 2017b).

Key Competencies	Descriptions of the Key Competencies
Systems thinking	The ability to understand relationships, analyze complex systems, consider different systems and scales, and deal with uncertainty
Anticipatory competency	The ability to understand and assess the possible, probable, and desirable futures, create one's own future prospects and apply the precautionary principle to them, assess the consequences of actions, and deal with risks and changes
Normative competency (competency concerning norms and rules)	The ability to understand and examine the community and societal norms and rules underlying actions, to negotiate values, principles, and goals of sustainable development, and to deal with uncertain information and contradictions
Strategic competency (Competency in matters central to the school's goals)	The ability collectively to develop and implement innovative actions that promote sustainability at the local level and beyond
Collaboration competency	The ability to learn from others; understand and respect the needs, perspectives, and actions of others (empathy); understand and be sensitive to others (emphatic leadership) and handle conflicts in a group and facilitate collaboration and participatory problem-solving
Critical thinking competency	The ability to question norms, practices, and opinions; examine one's own values, perceptions, and actions and participate in the sustainable development debate
Self-awareness competency	The ability to examine one's own role in the local community and (global) society to continuously evaluate and motivate actions, and to process emotions and desires
Integrated problem-solving competency	The ability to apply different problem-solving frameworks to complex sustainability problems and develop applicable, inclusive, and equitable solutions contributing to sustainable development integrating the above-mentioned competencies

Competency in sustainability research and problem-solving means having the knowledge, skills, and attitudes necessary for successful task performance and problem-solving with respect to real-world sustainability challenges and opportunities (Wiek et al., 2011). To solve real-world sustainability challenges, five key competencies are introduced, namely systems thinking competency, anticipatory competency, normative competency, strategic competency, and interpersonal competency. Interpersonal competency was later renamed collaboration competency, and three new competencies were added to the list (UNESCO, 2017b).

In science subjects, including biology, scientific (science) literacy and evolutionary literacy are also seen as important key competencies. *Scientific literacy* includes both conceptual understanding of the processes and epistemology and understanding of the nature of science (Roberts, 2007). The nature of science (NOS, Erduran & Dagher, 2014) refers to the understanding of what the general principles that characterize natural science are and what scientifically valid knowledge acquisition is like. According to Roberts and Bybee (2014), to be scientifically literate means to understand how science works in practice. This includes understanding how scientists conduct research and collect data, as well as understanding the processes scientists use to ensure the validity and reliability of their findings. Scientifically literate citizens understand the nature of symbolic systems of representation and expressions, are aware of their own socioscientific ways of thinking, and know how to relate their actions to their own and society's needs. They are able to apply biological content knowledge in their everyday lives.

Evolutionary literacy is essential for planning and achieving a sustainable future (Pessoa et al., 2024). The development of evolutionary literacy requires the ability and willingness to learn continuously (prospective learning, Vogelstein et al., 2022). It is based on the predictive ability to see cause-and-effect relationships of what actions should be taken to achieve better outcomes (UNESCO, 2017a).

In biology education, teachers can foster the development of students' competencies and skills by using different educational approaches, such as disciplinary, interdisciplinary (Lozano et al., 2017), multidisciplinary, and transdisciplinary approaches (Molthan-Hill et al., 2022). *A disciplinary approach* provides detailed insights within a single field, allowing for a deep understanding of specific aspects, such as climate change or biodiversity. *An interdisciplinary approach* deepens knowledge of individual disciplines across the STEM fields (science, technology, engineering, and mathematics), providing a broad understanding needed to solve real environmental problems (White et al., 2024). *A multidisciplinary approach* combines different perspectives from different fields and subjects in education (also including, for example, language education) and integrates these insights to form coherent strategies (Persano Adorno et al., 2025). *A transdisciplinary approach* promotes collaboration with external stakeholders by addressing environmental challenges holistically across sectors (Chopra et al., 2019). Focusing on key competencies, such as systems thinking and anticipatory competencies (Palmberg et al., 2017; Pessoa et al., 2024; Yli-Panula et al., 2021), biology education can support students' understanding of and action competence for sustainable development.

2.3.2. Subject Aims and Learning Objectives

The key biology subject aims include aims related to the development of factual and conceptual knowledge (Erduran & Dagher, 2014), scientific skills (Dogan & Kunt, 2017), environmental attitudes (Kahveci, 2023), and environmental awareness and feelings (Ballard et al., 2024; Gazoulis et al., 2022). In line with the aims of science education, it is important to also determine the subject aims concerning nature and living organisms so that students are able to conduct research and apply the knowledge to their daily life. Teaching

should also strengthen the fascination and joy of discovery, as well as the human sense of wonder and curiosity towards all living things. Thus, the subject aims should promote making knowledge and experiences useful in fostering a sense of care and respect for nature and for our fellow human beings. They should increase the student's understanding of living systems and allow them to consider the systems in relation to themselves and other organisms in the natural environment.

According to Kärnä et al. (2012), students are best at factual and conceptual knowledge, i.e., the basic levels of systems thinking. Tasks that require the application and analysis of knowledge are challenging for students. Therefore, in addition to factual and conceptual knowledge, it is important to also define other subject aims, such as psychomotor (Lewinsohn et al., 2015) and affective learning (Ballard et al., 2024; Gazoulis et al., 2022).

2.3.3. Learning Objectives in Relation to Competency Objectives

Defining learning objectives facilitates the selection and organization of content and enables the assessment of learning outcomes. According to Rodriguez and Albano (2017), there are four types of learning objectives: institutional, program-specific, course-specific, and instructional. Institutional objectives address what students can expect from their studies at an educational institution. Program-specific objectives describe the knowledge and skills students are expected to acquire during their education. Course objectives describe what students can expect to learn in a course. Instructional objectives describe what students should know and be able to do and allow for the assessment of student learning in relation to course objectives.

Learning objectives affect students' understanding of ecological processes. For example, during a longitudinal study (Heldén & Heldén, 2008), it has been found that early episodes in childhood in many cases seem to have an important influence on the students' future learning about scientific phenomena. One way to support students' understanding of environmental problems caused by human activity is to integrate SE into biology teaching, with the aim of increasing their environmental awareness. This may support students to recognize the ecosystem's crucial meaning for human life and for global sustainable development.

Learning objectives promoting sustainable development are related to the development of understanding phenomena, functional skills, collaboration skills, critical thinking skills, problem-solving skills, and research skills. The learning of these skills can be supported by arousing students' interest and motivation in learning biological topics related to sustainable development (Yli-Panula et al., 2024). Central for defining learning objectives are competency objectives concerning strategic action. Examples of how the competency objectives promoting sustainable development can be related to the learning objectives in biology education are presented in Table 3.

Table 3. Competency objectives promoting sustainable development related to learning objectives in biology education.

Competency Objectives (SDG = Sustainable Development Goal) (UNESCO, 2017a, 2017b)	**Examples of Learning Objectives in Biology Education (Uitto et al., 2024a)**
To develop students' systems thinking and ethical thinking (SDGs 12–15)	To understand ecological systems and biodiversity and the importance of their conservation in relation to technological, social, and economic systems; understanding the structure, function, and interactions of living nature from the molecular and cellular levels to the biosphere

Table 3. *Cont.*

Competency Objectives (SDG = Sustainable Development Goal) (UNESCO, 2017a, 2017b)	Examples of Learning Objectives in Biology Education (Uitto et al., 2024a)
To examine the past, present, and future in terms of evolution, ecological systems, and the preservation of biodiversity, and to reflect on human well-being and responsibility in relation to nature and other people (SDG 17)	To develop capabilities for studying and working in fields that utilize biology; understanding the opportunities offered by life sciences to promote the well-being of humanity, other organisms, and living environments; increasing understanding of how biological knowledge can be utilized in everyday life, in postgraduate studies, and in working life
To understand the standards for sustainability education stated in curricula (SDG 17)	To reveal the image of the necessity of a sustainable lifestyle and the importance of a circular economy that saves natural resources
To develop and implement activities in the school's immediate environment to promote student learning and well-being (SDGs 4, 5, and 16)	To develop the student's capacity to influence and participate from the perspective of developing their own local environment and ensuring its vitality; support a sustainable lifestyle in the student's own local environment
To develop student identity by incorporating collaborative inclusive learning into teaching, promoting collaborative interaction within the school community, and developing collaborative learning environments (SDG 17)	To develop students' cooperation skills and sense of community by using interactive working and operating methods
To develop students' critical observation skills, critical thinking, and critical reading skills (SDG 17)	To develop an understanding of how biological knowledge and skills can be applied and utilized in one's own life, in ethical considerations and in following current news related to biology; developing a critical examination of various phenomena and sources of information; developing a critical evaluation of biological information transmitted through the media
To support students' self-assessment skills and ability to reflect on themselves as learners and develop students' self-regulation skills, sense of competence, self-respect, and self-direction (SDG 5)	To support students in understanding themselves and other people and setting their own goals
To develop students' problem-solving skills and encourage students to engage in problem-solving and argumentation (SDG 17)	To support students' problem-solving skills; supporting the formulation of questions and research problems regarding the phenomena under study

2.3.4. Knowledge Categories and Knowledge Types

According to Harlen et al. (2010), biology is based on four big ideas. (1) Organisms are organized on a cellular basis. (2) They require a supply of energy and materials, for which they are often dependent on, or in competition with, other organisms. (3) Genetic information is passed down from one generation of organisms to another. (4) The diversity of organisms, living and extinct, is the result of evolution.

Biology contains a number of key concepts, some of which are also found in chemistry and physics, such as the flow of energy and the circulation of materials. However, many key concepts are specific to biology, such as reproduction, heredity, evolution, and homeostasis. All organisms are able to regulate their internal environments to a very considerable degree, although this is more apparent in some types (e.g., most mammals and birds) than in others (Reiss & Winterbottom, 2023).

The big ideas and the key concepts form the basis of subject matter content knowledge (SCK). Additionally, a teacher must have curriculum knowledge and understanding of the principles of related teaching activities; in other words, pedagogical content knowledge (PCK) (Shulman, 1986). According to Shulman (1986), SCK is the teacher's knowledge

of the content and structure of a subject. Curriculum knowledge includes knowledge of curricula, learning materials, and knowledge of what is to be taught in the subject area. PCK is information about how the subject matter to be learned should be formulated so that students understand it (Shulman, 1986). Table 4 provides examples of how SCK and PCK relate to knowledge categories and types. Understanding and solving environmental problems requires both SCK and PCK related to planetary boundary conditions (Rockström & Sukhdev, 2016). Planetary boundary conditions are the boundary values that define a safe operating range for humanity within the framework of biological and physical systems (Rockström et al., 2009).

Table 4. Knowledge categories and types (Shulman, 1986; Yli-Panula et al., 2025).

Knowledge Categories	Definition	Knowledge Types	Related to	
			SCK	PCK
Factual and Conceptual knowledge	Factual knowledge is common knowledge about what is needed to be successful to meet a goal. Conceptual knowledge consists of knowing how facts can be organized in meaningful ways.	Knowledge of classification	×	
		Knowledge of principles and generalizations	×	
		Knowledge of theory, models, and structures	×	
		Knowledge of terminology	×	
		Knowledge of details and basic elements	×	
Methodological knowledge	This information concerns how to do something or how to solve a problem, such as a learning task (Osborne et al., 2018). It is also information about research methods, such as how to make observations and study life phenomena.	Knowledge of skills, technical methods concerning subjects		×
		Knowledge of usage criteria		×
Metacognitive knowledge	This is a teacher's knowledge (Krathwohl, 2002) and student's knowledge about how they can manage their own learning and plan their studies (Krathwohl, 2002; Pintrich, 2002).	Knowledge of strategies, usage of methods, and self-awareness		×
Evaluative knowledge	This is systematically collecting and analyzing information. It is linked to evaluative thinking, a disciplined approach to inquiry and reflective practice that helps people to make judgements with good evidence by habit (Cole, 2023).	Knowledge of understanding interactions and performance		×
Critical reflection and reflective knowledge	Critical reflection is a 'meaning-making process' that helps people to set goals and use what they have learned to inform future actions and consider the real-life implications of their thinking. It links thinking and doing and can be transformative (Rodgers, 2002; Schön, 1992). Reflective knowledge is an actor's ability to evaluate their epistemic position and the circumstances of knowing. It is part of the belief formation process and confirms the overall process of knowing (Broncano, 2014).	Knowledge of reviewing, reconstructing, re-enacting, and critically analyzing		

There are many relevant issues regarding teaching and learning sustainable development in biology education. According to Vision I, knowledge of biology includes understanding of what and what kind of biological phenomena are, how and why they

occur, and how biology as a scientific discipline studies life phenomena using scientific methods (Uitto et al., 2024a). This kind of knowledge can be seen as teachers' subject matter content knowledge (SCK) (Shulman, 1986). In Agenda 21 (UN, 2003) and the 2030 Agenda for Sustainable Development (UN, 2021), the following issues are listed: soil/land degradation; desertification; biodiversity/biodiversity loss; climate change; water/oceans; poverty and justice; health and food; consumption; gender differences/gender equality; and housing/safe, resilient, and sustainable human settlements and participation. The UN (2003) mentions environment and development; pollution; agriculture; biotechnology; and new technologies. The UN (2021) also emphasizes protection of ecosystems, sustainable energy, and sustainable industrialization. In SE, the starting point for learning should be learning the names of things (Jensen, 2025) because it is the first step toward ecological literacy.

Ecological literacy is based on science and sustainability knowledge. It includes conceptual knowledge, meaning understanding individual concepts as well as broader conceptual issues and their connections (Krathwohl, 2002). For example, the concept of ecosystems is related to environmental issues such as the use of fossil fuels, global warming, population growth, and soil degradation. Ecological literacy may help people to understand environmental issues at the local, regional, and global levels (Bleier, 2021). It also includes an attitude of caring about the environment and the tendency to act on the basis of environmental knowledge and feelings. It refers to applying ecological knowledge and problem-solving approaches, enabling solutions based on ecological science (Lewinsohn et al., 2015).

Previous research has shown that environment-based learning can enhance students' awareness and understanding of sustainability concepts and systems thinking (Palmberg et al., 2017). According to Jensen (2025), it is important to educate growing generations to be knowledgeable about ecological concepts that bind species, human beings included, together. Systemic concepts regarding photosynthesis, food production, natural and human-made climate change, biodiversity, and ecosystem services need to be embraced, like the understanding of systemic interrelatedness in ecosystems, such as thermodynamics, nutritional cycles, and population dynamics (Jensen, 2025). Insufficient ecological awareness is closely linked to environmental challenges.

SE has tended to focus on good practices within business-as-usual approaches, such as environmentally friendly consumer choices regarding food, transportation, and recycling (Jensen, 2025). However, making environmentally friendly choices does not foster agency outside the private sphere. Models of science education have changed over the years. Competency-based models, such as PISA, focus on key skills: explaining phenomena scientifically, evaluating scientific research, and interpreting evidence in real-world settings regarding the conscious connection of a person's cognitive and linguistic abilities with their sense of place and a well-founded self-awareness of their place in the world (Jensen, 2025). At the core of this view is powerful knowledge. According to Young (2009), powerful knowledge is distinct from common sense knowledge, systematic and specialized. This means that powerful knowledge can serve as contexts (OECD, 2017). The "contexts" component moves science education from content-focused approaches to applying knowledge in different contexts and to attitudes that support application (Kumar & Kumar Choudhary, 2025). The PISA 2025 framework introduces a "science identity" that emphasizes students' perception of themselves as capable scientific participants (OECD, 2023) to critically address societal issues.

For a deeper understanding of one's own and humans' role and position in relation to the ecosystem and for evoking students' agency as future responsible citizens and decision-makers, according to Vision II, it is important to apply biology knowledge in a person's

own life and as a member of society (Uitto et al., 2024a). For this, one needs methodological knowledge (Krathwohl, 2002), knowledge about how observations about the biological phenomena and critical reflections based on sufficient scientific knowledge are made, how something is done, and how a problem can be solved.

According to Vision III, the goal of learning is action competence. Competence can generally be defined as having the experience, knowledge, and self-awareness to attend to a task effectively, with agility, under any circumstance, and to do so ethically (Lawrence et al., 2023). These three constructs are interdependent and all equally important. In the case of action competence, competence refers to the ability to acquire the relevant knowledge, along with the willingness (i.e., commitment and passion) to take action, confidence in one's own capacities for change, and confidence to take relevant action (Sass et al., 2020). It can be seen as integrated sustainability competencies and skills, attitudes to solve a real-world problem, and knowledge (Demssie et al., 2019). Action-oriented knowledge includes knowledge about the root causes of a problem and knowledge about strategies for change (Lampert et al., 2025).

Knowledge in biology is crucial when teaching sustainability (Uitto et al., 2024a). Metacognitive knowledge is the teacher's knowledge and the student's knowledge about how they manage their own learning and life (Krathwohl, 2002). Evaluative and reflective knowledge are typical for *lexical ecological literacy.* The concept provides a basis for generalization and thinking outside specific contexts or cases.

Powerful knowledge that relates to the goals of Visions II and III supports students to find reliable explanations for phenomena and new ways of looking at the world and possibilities to participate in social and ethical debates. Subject-specific educational content knowledge (Hudson et al., 2023) is essential for teaching and learning science subjects, including biology. Biology content areas such as ecology, biodiversity, and evolution can be combined with reflections on natural values, human health, and well-being in accordance with Vision II (Aivelo & Uitto, 2021; Sá-Pinto et al., 2022; Tidemand & Nielsen, 2017; Yli-Panula et al., 2022b). Many topics are connected to ecological, social, and economic sustainability (Uitto & Saloranta, 2017; Yli-Panula et al., 2022b). Ecology is related, e.g., to land use, production and consumption of commodities, nature loss, and ways to protect biodiversity. Biology topics can also link to social sustainability themes, such as human rights and equality, as stated in Vision III. The topics related to the well-being of humans and nature can appeal to attitudes or emotions and thus be sensitive to be taught (Ottander & Simon, 2021; Tidemand & Nielsen, 2017). Visions I–III for science education yield outcomes for the content and culture of science education, including biology education. To realize all three visions, teachers need both SCK and PCK.

2.3.5. Teaching and Learning Methods

Based on the classification criteria chosen, teaching and learning methods can be classified in different ways. According to Landøy et al. (2020), due to the large number of activities and their different variations, the same method can belong to different categories. In the most popular classifications, the main criteria are the person(s) to whom the teaching activity is directed, the type of training/lesson, the type of main activity, the degree of activity or passivity of the students, and the prevailing means of communication (oral or written). Based on the degree of activity of the individual at the center of the teaching activity, three types of teaching and learning methods are distinguished: teacher-centered, interactive, and student-centered methods (Landøy et al., 2020). Table 5 presents examples.

In teacher-centered (traditional) methods, the teacher is the primary authority and source of information. The teacher sets the ground rules for the classroom, presents the content to be learned, and creates both lesson plans and assessments. The teacher

explains the objectives of the lesson and provides feedback to the students, but the students are responsible for implementing the plans. Examples of this type include lectures and teacher presentations.

Table 5. Teaching and learning methods (information and communication technology, ICT; artificial intelligence, AI) (Ghafar, 2023; Kesler, 2020; Landøy et al., 2020; Södervik, 2024; Yli-Panula et al., 2018).

Teaching and Learning Methods		
Teacher-Centered Methods	**Interactive Methods**	**Student-Centered Methods**
Lecture-based - oral - written - video - instruction - explanation and demonstration - story telling	Skill-based - conversation - discussion - argumentation - exercise (drill and practice) - modeling - field trips - project-based learning- - case analysis and case study - field work - experiments - educational games - knowledge building learning - cooperative learning	Methods of organizing information and graphics: Visualization - conceptual map - diagrams Methods of stimulating creativity: - brainstorming - panel discussion - experiential learning - discovery learning - problem-based learning - inquiry-based learning - creative problem-solving - collaborative learning - service-design process ICT - simulations and animations - design-oriented learning - extended Reality - ChatGPT - virtual learning - AI

On the other hand, interactive methods refer to methods of teaching that engage the classroom. Unlike memorization, interactive teaching encourages students and teachers to collaborate to foster learning. Interactive methods include, for example, discussions and field trips.

The third type includes student-centered methods, which are based upon the concept of constructivism, where students can confer meanings to what they learn by relating new information to what they already know. This type of method includes, for example, research-based working methods and learning outside the classroom.

In addition to traditional teaching methods, student-centered methods are also used today more than before. Different problem-based teaching and learning methods and problem-solving outdoor education and learning are important ways to foster understanding for sustainable development (Yli-Panula et al., 2018).

Problem-based learning (PBL) is a student-centered approach to learning that involves groups of students working together to solve a real-world problem. Through PBL, students strengthen their teamwork, communication, and research skills and also sharpen their critical thinking and problem-solving skills, which are essential for life-long learning (Kurt, 2020). In PBL and inquiry learning, students define their own goals and study independently and self-directedly, after which they return to the group to discuss and refine the knowledge they have acquired. Students' interests, knowledge, attitudes, and behaviors concerning sustainability can be improved via problem-based activities and learning-by-

doing (Liefländer & Bogner, 2018). Collaborative learning supports students' acquisition and internalization of knowledge via active participation in groupwork while searching for information and while discussing the information found (Yli-Panula et al., 2018).

Woods et al. (2024) propose that learning should be conducted with a place, rather than about it, and the effects of students' own behavior should be discussed and sustainable actions practiced in local surroundings. Field-based activities, such as field trips and field work, provide students with authentic interactive experiences and experiential learning opportunities (Yli-Panula et al., 2018). Field work is defined as "any component of the curriculum that involves leaving the classroom and learning through first-hand experience" (Boyle et al., 2007, pp. 299–300). It develops students' observation skills, increases their interest and attainment, and improves their cognitive learning (Randler & Bogner, 2006). These are also crucial factors in promoting sustainable development.

Experiential learning is authentic first-hand sensory-based learning through a specific experience. It supports deep cognitive understanding by providing hands-on experiences that connect students to local and global ecosystems (Czajkowska & Ingaldi, 2023; Kiewra et al., 2023). Through active environmental activities with engagement with real-world sustainability challenges, affective experiences can strengthen ecological awareness (Lovren & Jablanovic, 2023) and encourage participation (Firinci Orman, 2024). Personalized experiential learning allows students to engage with real-world sustainability challenges in authentic and meaningful ways and provides opportunities to develop a deeper understanding of the multifaceted aspects of sustainable development. Immersive experiences likely influence students' attitudes toward sustainability (Murti et al., 2025) and foster a deep sense of environmental responsibility (Friman et al., 2024). Experiential and research-based outdoor learning also support understanding the importance of biodiversity by taking a responsible approach to nature and taking action to conserve biodiversity (Wolff, 2022), as well as understanding the impacts of one's own actions. Sensory and musical teaching and learning methods can strengthen a "nature feeling" or "nature connection" (Jensen, 2025).

Information and communication technology (ICT) and advanced technologies, as well as students' increased access to digital devices in schools and at home, have opened up new opportunities for visualizing and experimenting with phenomena (Yli-Panula et al., 2019). Digital literacy has emerged as a core skill in science education. In biology education, digital literacy is understood as the use of digital tools for acquiring information, as well as understanding and investigating biological concepts and phenomena (Bennett & Saunders, 2019).

Mobile learning technologies, including educational apps, virtual laboratories, and online platforms, offer a diverse and interactive approach to biology teaching and learning (Sangur et al., 2025). Mobile learning is an approach that integrates technology and user interaction to provide access to educational resources without the constraints of time and space, using devices such as smartphones, tablets, computers, and laptops (Singh & Suri, 2022). It is a part of learning that functions as a learning medium to improve critical thinking and student motivation and increase student self-confidence and satisfaction as users (Song & Cai, 2024). Beyond mobile learning, other digital learning technologies have emerged over the decades.

Various applications of extended reality (XR) (augmented reality, AR; virtual reality, VR; and mixed reality, MR) offer the opportunity to examine things and phenomena that are otherwise out of reach or to perform various experimental learning tasks (Alnagrat et al., 2022; Kapp et al., 2020; Södervik et al., 2021). AR learning environments enable the examination of microscopic things and processes, e.g., cell structures and cell division, and molecular biology (Bennett & Saunders, 2019; Reen et al., 2022). They can also be used to observe places and time dimensions (e.g., anoxic lake bottoms or melting

glaciers) that would otherwise be inaccessible (Södervik, 2024). Virtual nature experiences can in some situations be as effective in supporting environmentally friendly behavior as learning situations that take place in real nature (Deringer & Hanley, 2021). Virtual learning can increase student motivation and support learning (Bennett & Saunders, 2019; Kapp et al., 2022). The use of artificial intelligence (AI) in education is also increasing, and students will need so-called AI literacy later in life (Toivonen, 2023). AI literacy is the ability to understand, use, monitor, and critically reflect on AI applications (Laupichler et al., 2022). AI can be used, e.g., to create learning tasks that are appropriate for the students' competencies and that develop their ethical thinking and empathy skills (Chiu et al., 2023).

In biology education, teaching and learning methods should be selected for supporting learning biology, learning to conduct biological science, and learning about biological science. Different learning environments and topical and contextual tasks can promote meaningful learning. Studies have found that changing the learning environment from traditional to digital can support learning. For example, combining augmented reality learning environments (e.g., a virtual laboratory) with a traditional learning environment (e.g., a regular school laboratory) may support learning better than either learning environment alone (Södervik, 2024). Collaborative technology increases high-level cognitive and social interaction when students work together to achieve deeper understanding (Hakkarainen, 2003).

2.3.6. Evaluation and Assessment

Comprehensive evaluation is an important part of teaching and learning processes. It provides teachers with information regarding students' interest in the topics covered in biology education and how, as a result of teaching, they have been able to build, for example, values related to sustainable development. Assessment practices are integral to pedagogy and learning outcomes (Vahed et al., 2023). Effective curriculum design requires the integration of assessment, teaching, and feedback to enhance student achievement (Ali, 2018). Assessment tasks provide students with opportunities to reflect on their learning experiences, develop theoretical knowledge, and apply their understanding to real-world contexts.

There are three types of assessment: diagnostic, formative, and summative. Diagnostic assessment maps the starting level of learning and students' preconceptions (Atjonen, 2017; Södervik, 2024). Formative assessment is an ongoing process that focuses on activities during the learning process and supports students in building conceptual understanding (Veugen et al., 2021). Summative assessment, on the other hand, typically takes place at the end of the learning process. It examines how the learning objectives are achieved and at what stage of the process of conceptual change the student is (Atjonen, 2017; Södervik, 2024). It serves purposes such as accountability, ranking, and certifying competence (Schellekens et al., 2021). The interplay between formative and summative assessments underscores the importance of continuous assessment in guiding students toward understanding their progress in the acquisition and internalization of knowledge.

Teachers must identify different levels of learning from the content being studied, demanding that the content areas and the teaching and assessment are planned in line with these levels when assessing the construction of the students' conceptual understanding (Bloom et al., 1956; Krathwohl, 2002). Factual and conceptual learning can be assessed with tasks that measure knowledge (e.g., gap tasks and concept definition tasks) (Södervik, 2024). By focusing on systems thinking, such tasks allow for an examination of the extent to which the students have understood concepts and are able to explain phenomena scientifically. In biology teaching, learning according to Vision I can be assessed, for example, by examining how the students understand, apply, analyze, evaluate, and present information about the

structure and function of ecosystems, ecosystem services, and nature conservation (Uitto et al., 2024b).

More demanding learning tasks are needed in assessing the students' deeper knowledge of the subject and their ability to apply what they have learned. Learning methodological knowledge according to Vision II can be assessed based on the students' outputs. In the students' essays, portfolios, and project reports, a key assessment item can be how the students apply the knowledge to commonly encountered and important problem-solving situations (Södervik, 2024). By examining how they evaluate, for example, the forest environment and its use based on biological knowledge from the perspective of their experiences and hobbies, it is possible to assess the students' knowledge of the subject, critical evaluation of different perspectives, presentation of arguments based on scientific knowledge (Uitto et al., 2024b), and ability to apply what has been learned, possibly across subject boundaries (Södervik, 2024).

Learning metacognitive, evaluative, and reflective knowledge according to Vision III can be assessed by examining the development of the students' action competence from the perspective of promoting sustainability (Sjöström & Eilks, 2018). For assessing in-depth conceptual understanding and change, open tasks provide an opportunity to understand the students' thinking. A way to assess deep conceptual understanding and conceptual change is through practical work by focusing on integrated problem-solving (Aleknavičiūtė et al., 2023). In biology teaching, it can be assessed, for example, how the students integrate ecological, social, and economic perspectives of sustainability into their activities, how they accept different perspectives (pluralism), and how action-oriented they are (Olsson et al., 2022; Uitto et al., 2024b).

3. Research Aim and Questions

Although a fair amount of research has been published on biology teaching and sustainable education (SE), there is a lack of research-based information from a holistic viewpoint on biology education that includes sustainable development in teacher education and school teaching. In this study, sustainable development goals, subject aims and learning objectives, knowledge, teaching, and learning methods, and competencies and skills are clarified and described for promoting sustainable development in biology education. In addition, assessment methods are explored for fostering sustainability competencies and skills. Figure 1 presents the research questions of this study in relation to the theoretical background.

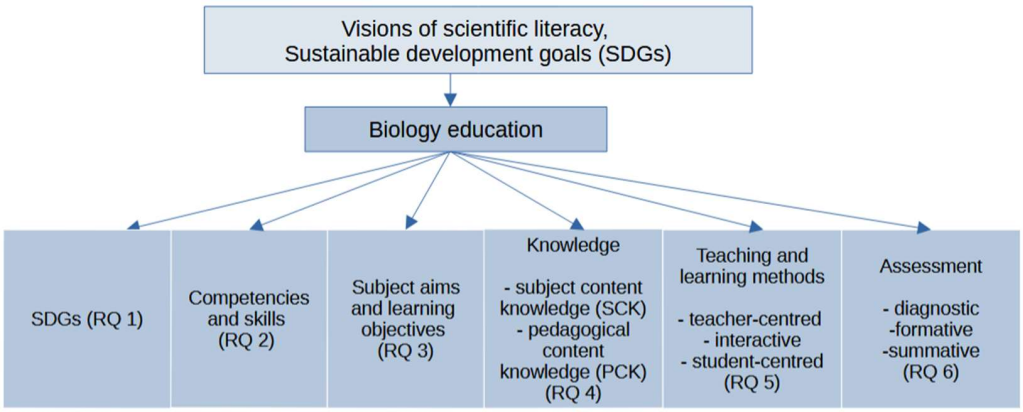


Figure 1. The research questions in relation to the theoretical background.

This study is based on the following RQs:

(1) Which of the UN sustainable development goals (SDGs) have been included in biology education?
(2) Which kinds of competencies and skills promoting sustainable development have been included in biology education?
(3) Which kinds of subject aims and learning objectives promoting sustainable development have been included in biology education?
(4) Which kinds of knowledge promoting sustainable development have been included in biology education?
(5) Which kinds of teaching and learning methods promoting sustainable development have been included in biology education?
(6) Which kinds of assessment methods fostering sustainability competencies and skills have been included in biology education?

The findings are expected to contribute to the development of biology education promoting sustainable development in teacher education and school teaching to support the shift towards sustainable living and well-being.

4. Materials and Methods

In this study, the focus is to clarify how sustainable education (SE) teaching and learning ideas have been incorporated into sustainable development-focused biology education. The study is qualitative with some quantitative elements. The detailed steps in conducting data analysis are illustrated in Figure 2.

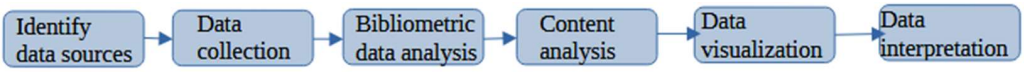


Figure 2. Steps in conducting data analysis.

4.1. Selection of Materials

The material was selected by applying the method presented by Àlvarez-Garcia et al. (2015). For a systematic review, peer-reviewed documents were selected using a consistent search strategy, criteria were established for the selection of documents to be considered, and the documents were analyzed based on clear and precise criteria and aspects (S. Green et al., 2011).

The documents published between 1 January 2000 and 31 December 2024 were searched from the database Scopus. Scopus is a comprehensive multidisciplinary abstract and citation database covering multiple scientific disciplines, including social, physical, health, and life sciences. Compared to more restricted databases, it offers extensive comprehensive coverage of peer-reviewed literature, conference proceedings, and other scholarly sources (Donthu et al., 2020).

The search strategy was based on a systematic organization, categorization, and selection of keywords related to biology education, biology curriculum, teaching and learning objectives, powerful content knowledge, teaching resources, teaching methods, evaluation and assessment, students' outcomes and competencies, implications and impacts, research gaps, sustainability, sustainable development, sustainable development goals, and 2030 Agenda. Using these keywords, a hierarchical search strategy was applied, starting from the simplest expression (one term) to the most complex form (combinations of terms using Boolean operations). All searches were conducted in English between 6 April and 9 May 2025.

When selecting material for the analyses, the following criteria were used:

(a) Language: English;
(b) Period: 2000–2024;

(c) Scope: national and international publications;
(d) Educational levels: primary, secondary, and higher education;
(e) Types of studies: documents in biology education that provide concrete support to the development of biology curricula and teaching;
(f) Quality: academic studies.

The sample selection process adhered to the flowchart shown in Figure 3, which aligns with previous studies (Yli-Panula et al., 2018, 2020a, 2020b). During the first phase (Identification), 1683 documents were retrieved from the Scopus database using each key term's "article title, abstract, and keywords" search option without limiting the document type. In the second phase (Screening), the search was refined to include only the articles, book chapters, and books with sufficient pertinence or adequate interdisciplinary coherence, reducing the number of documents to 175. Then, duplicates were removed, bringing the final number of documents to 165 (119 articles, 45 book chapters, and 1 book).

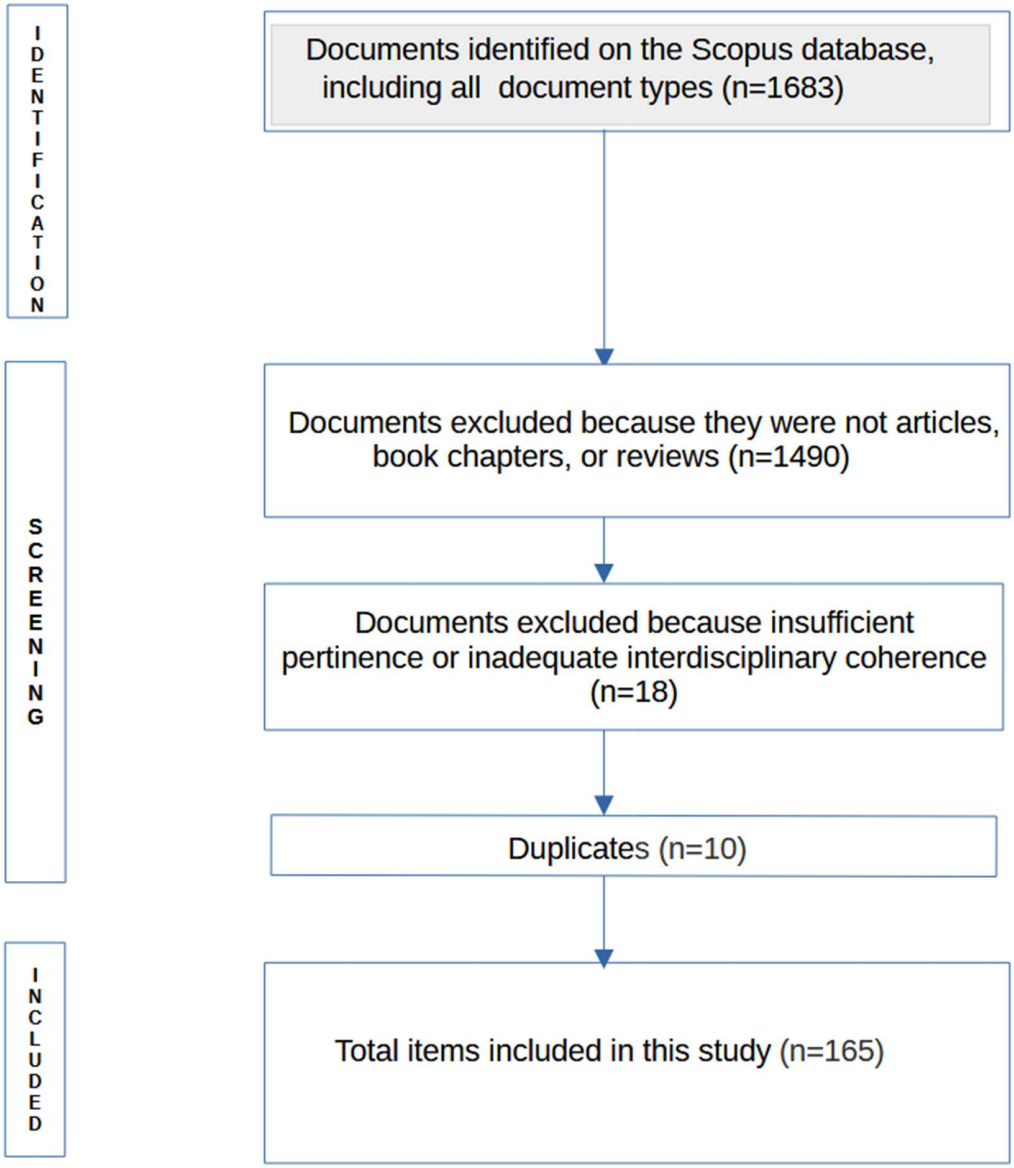


Figure 3. The process of selecting publications for bibliometric analysis (figure by the authors).

Mixed types of sources were selected for the data analysis in order to obtain the most comprehensive picture of the current situation in biology education for supporting sustainable development in teacher education and primary and secondary school education.

4.2. Analysis Methods

The data analysis was carried out in two phases: a bibliometric analysis, followed by a qualitative content analysis. The clusters produced by the bibliometric analysis produced a general description of the research topics. Then, content analysis was used to search for meaningful views on the phenomenon under study and to find ideas for developing biology education focused on sustainable development in teacher education and school teaching.

4.2.1. Bibliometric Analysis

To identify the state of SE in biology education studies, a bibliometric analysis based on the titles and abstracts of the studies was performed. An artificial intelligence (AI)-assisted approach was used.

In the long run, the main reason for introducing AI tools for bibliometric analysis is scalability. During the last few years, the scope of scientific activity has significantly expanded, making it increasingly difficult for an unassisted human to keep up with the latest research. Traditional human-made reviews are limited by time and attention considerations, whereas AI tools can operate quickly and on much larger datasets.

Another long-run consideration is that AI tools enable agile reviews. By moving the workload of reviewing existing studies from human experts to AI systems, a researcher with access to an online article database can perform on-demand automatic reviews of specific topics, expediting access to a synthesis of the latest scientific knowledge.

In the near term, however, the effectiveness of such AI tools needs to be validated. This study looks at a traditional small dataset using a complementary combination of AI-powered and traditional manual analysis. The initial clustering was performed by AI, and then each automatically detected cluster was manually analyzed, named, and split into subtopics.

The automatic part of the bibliometric analysis was performed with Raven-visualizer (J. Jeronen, 2024), which is an open-source visual topic analysis tool for exploration of scientific literature.

The final result from the bibliometric analysis step was a two-dimensional semantic map clustering semantically similar studies together, thus facilitating the content analysis step. The process by which the software automatically produces the semantic map is based on small specialized AI models and statistical algorithms and is explained in detail in Appendix B.

The semantic map was visualized interactively in Raven-visualizer, displaying the two-dimensional data together with the corresponding metadata of the studies (from the original BibTeX dataset), as shown in Figure 4.

Additionally, Raven-visualizer was used to generate a word cloud from the dataset. The details of how the titles and abstracts were processed for the word cloud are explained in Appendix B. The resulting word cloud is shown in Figure 5.

The automatic clustering revealed six distinct clusters and eight outliers (individual data points), which did not fall into any cluster. The top-level grouping and cluster numbering follow the results of the automatic clustering. In addition to yielding a useful top-level grouping, this shows the current level of capabilities as well as limitations of the automatic clustering algorithm in the current version of the software used.

To provide an overall qualitative understanding of each cluster, the range of topics within that cluster was extracted by further manual content analysis of the titles and abstracts. These more specific topics are shown in the column labeled *Item topics* in Table 6. Studies that did not fit the top-level theme of the cluster that the automatic clustering placed them in are marked with the item topic *outlier*. Many such outliers were from other fields outside biology education. The reason these items were present in the dataset is that the online search engine had spuriously included them in the search results from which the dataset was constructed.

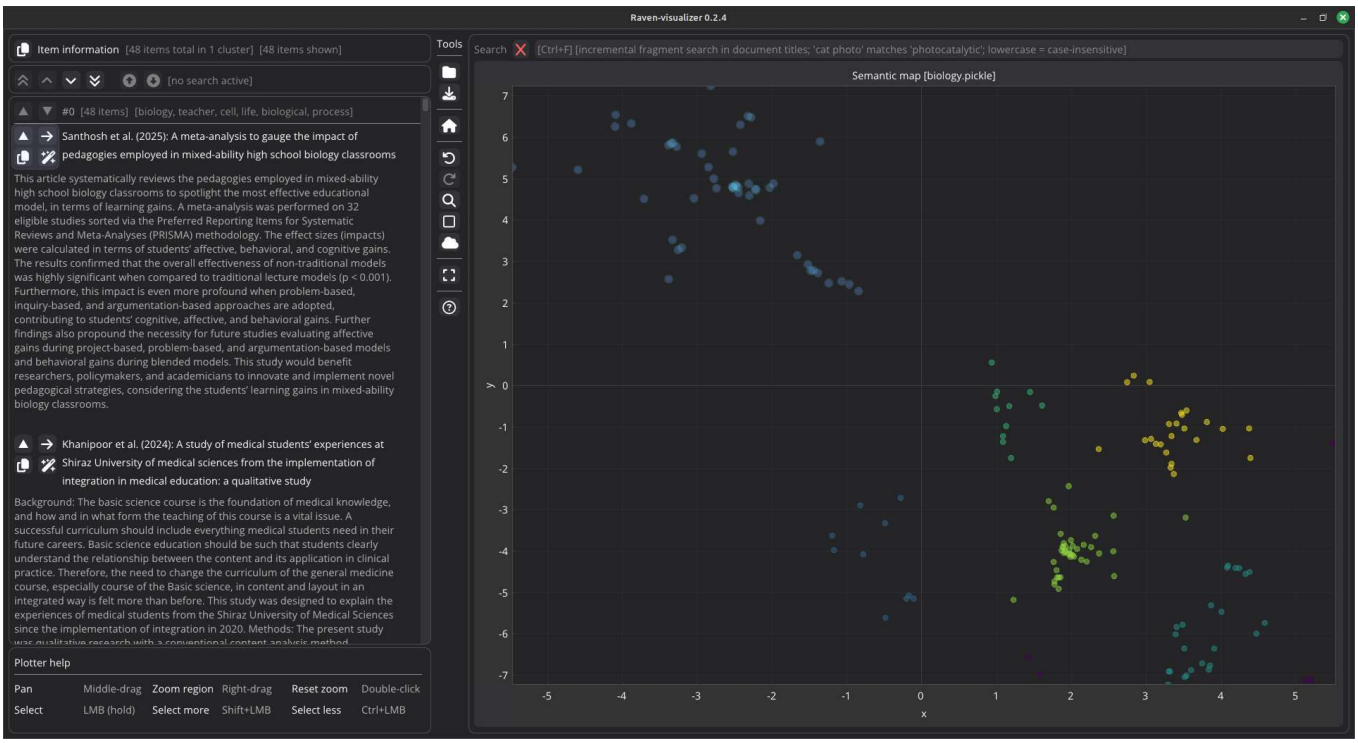


Figure 4. The two-dimensional semantic map for the dataset of this study (n = 165). In the visualizer, the dataset can be explored interactively. Semantically similar items are located near each other in the semantic map. The map is colored by the detected final clusters (screenshot by the authors).

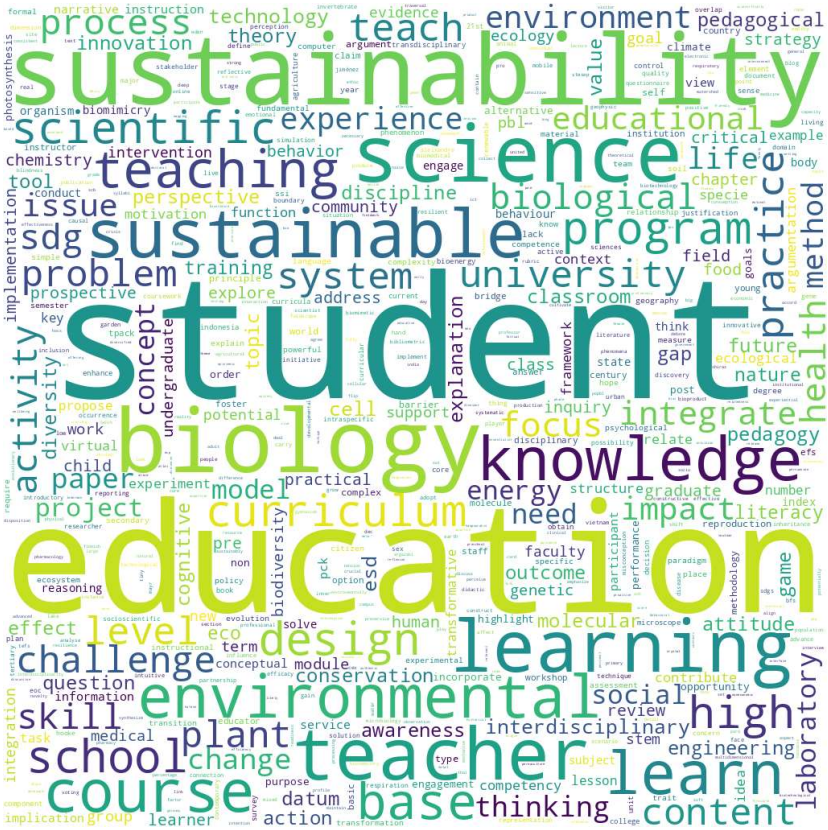


Figure 5. Word cloud, computed from the full dataset (n = 165). The words were automatically collected from the titles and abstracts, automatically cleaned up, and then plotted as a word cloud (figure by the authors).

Table 6. Clustered studies, topics of cluster items, cluster numbers, and topics.

Clustered Studies	Item Topics (*n*)	Count (*n*)	Cluster Number and Top-Level Topics
Assaraf and Snapir (2018); Byrne and Grace (2018); Carson et al. (2018); Duncan and Boerwinkel (2018); Gericke and El-Hani (2018); Hamman (2018); Kampourakis and Stasinakis (2018); Korfiatis (2018); McComas (2018); Millstein (2013); Nehm (2018); Reiss (2018); Sanders and Jenkins (2018)	Scientific knowledge (13)	49	#0 Biology education
Akpınarlı and Turan (2023); Ariely and Yarden (2018); Bass (2012); Cheng et al. (2021); Conde-Caballero et al. (2019); Courter (2012); Danilov and Danilova (2013); Driver et al. (2000); Ergazaki (2018); Evans and Rosengren (2018); Fuentes and Entezari (2020); Förtsch et al. (2018); Hamman (2018); Harland and Wald (2018); Harms and Bertsch (2018); Jiménez-Aleixandre and Evagorou (2018); Kampourakis and Niebert (2018); Khanipoor et al. (2024); Kwiek et al. (2007); Lederman (2018); Ledbetter (2012); López-Fernández et al. (2024); Power (2012); Reiss and Kampourakis (2018); Rozenszajn and Yarden (2015); Rutledge (2008); Schmitt-Harsh and Harsh (2017); Stern (2000); Stover and Mabry (2010); Susman (2015); Wanieck et al. (2020); Yoon et al. (2015)	Subject content knowledge (SCK) and pedagogical content knowledge (PCK) (32)		
Arita (2017); Livotov et al. (2021); Pessoa et al. (2024); Santhosh et al. (2025)	Outlier (4)		
Dönmez (2024); Schlicht-Schmälzle et al. (2024)	Sustainability and sustainable development policy (2)	13	#1 Sustainability, sustainable education (SE), and sustainable education goals (SDGs)
Brody and Ryu (2006); Capello et al. (2021); da Silva and de Araújo (2022, 2024); Faizah et al. (2024); Ferrer-Estévez and Chalmeta (2021); Ghazian and Lortie (2024); Mikhailova et al. (2024); Prieto-Jiménez et al. (2021); Wieërs et al. (2024)	SE and SDGs (10)		
Stevens et al. (2022)	Outlier (1)		
Abramovich and Loria (2015); Barraza and Castaño (2012); Bezeljak et al. (2020); Biletska et al. (2021); Desa et al. (2021); Edwards et al. (2015); Faizah et al. (2024); Leal Filho et al. (2016); Hartadiyati et al. (2019, 2020); Jeronen et al. (2017); Pimdee (2020); Purwianingsih et al. (2022); Putra et al. (2022); Rasmussen (2017); Sebastián-López and González (2020); Sidiropoulos (2018); Streiling et al. (2021); Suwono (2019); Yli-Panula et al. (2024); Weber et al. (2020)	Teacher education (21)	37	#2 Teacher education and school education
Al-Muqbil (2024); Amprazis and Papadopoulou (2024); Baena-Morales et al. (2023); Bara et al. (2024); Copeland Solas and Wilson (2015); Day et al. (2013); Fadzil and Saat (2020); Jackson et al. (2023); Mirosavljević et al. (2024); Muñoz-Galván and Padilla (2024); O'Neill et al. (2024); Quinn et al. (2015); Safitri et al. (2017); Thomas et al. (2022)	School education (14)		

Table 6. *Cont.*

Clustered Studies	Item Topics (*n*)	Count (*n*)	Cluster Number and Top-Level Topics
Hawa et al. (2021); Wright et al. (2008)	Outlier (2)		
Goi (2024); Galante et al. (2024); Tejedor and Segalas (2018); Warburton (2003)	Inter- and transdisciplinarity (4)	11	#3 Holistic view of sustainability education
Cabral and Kaivola (2005); Salovaara et al. (2021); Sterling (2004, 2010); Upton (2021); Wamsler (2020)	Transformative education (6)		
Medir et al. (2016)	Outlier (1)		
EI Kharki et al. (2021); Karimov et al. (2024); Kirkpatrick et al. (2019); Nersesian et al. (2021); Rodríguez-Loinaz et al. (2022); Thinh et al. (2024); Zhong and Liu (2022)	ICT (virtual, digital, ICT) (7)	32	#4 Learning and teaching methods in biology education
Araripe and Zuin Zeidler (2024); Carrió Llach and Llerena Bastida (2023); Hardyanto et al. (2024); Leite et al. (2016); Nkaizirwa et al. (2023); Sundberg et al. (2019)	PBL (6)		
Kennedy et al. (2015); Linder and Huang (2022); Veena Soni (2020)	Problem-solving (3)		
Mitra et al. (2016); Wolff et al. (2018)	PjBL (2)		
Rodríguez-Rey et al. (2024); Zoller (2015)	Inquiry-based learning (2)		
Adeika et al. (2024); Douglas et al. (2024); Gutiérrez-García et al. (2024); Hogan and O'Flaherty (2021); Kulshreshtha et al. (2022); Lebo and Eames (2015); Struminger et al. (2021); Wright et al. (2009); Zimmerman and Weible (2017)	Field work, field trip, and experiential learning (9)		
Gatti et al. (2019)	Game education (1)		
Muslu and Isik (2024)	Role-playing(1)		
Howell (2021)	Flipped classroom (1)		
Bacon et al. (2011); Brandt et al. (2021); Church and Skelton (2013); Chuvieco et al. (2022); Fisher and McAdams (2015); Fox et al. (2009); Gaard et al. (2017); Garibay et al. (2020); Gulikers and Oonk (2019); Kessler (2018); Le et al. (2022); Martens et al. (2010); McSorley et al. (2023); Mintz and Tal (2013); Papageorgiou et al. (2024); Rehman et al. (2023); Sherry (2022); Vandaele and Stålhammar (2022); Wiek et al. (2011)	Teacher education in sustainability, sustainability curricula (19)	25	#5 Sustainability competencies and skills
Wang et al. (2019); Zilberman et al. (2018)	Sustainability policy (2)		
Alordiah (2023); Du Toit (2024); Fayomi et al. (2019)	Research and teaching gaps (3)		
Paulauskaite-Taraseviciene et al. (2022)	Outlier (1)		

In the dataset, there can be overlaps between the topics. However, the software automatically assigns each paper only to a single cluster at most. Two such overlaps were manually identified, and the relevant studies were also manually assigned to the appropriate additional cluster or item topic. There are a total of 167 clustered studies in

Table 6, but the number of clustered references in the reference list in Appendix A is 165 because Hamman (2018) is included both in the scientific knowledge as well as in the content knowledge and teaching biology items within the biology education cluster (#0), and Faizah et al. (2024) is included both in the sustainability, sustainable education (SE), and sustainable education goals (SDGs) cluster (#1) as well as in the teacher education and school education cluster (#2). The clustered studies, item topics, count of items in each topic, and the cluster's top-level topics and cluster number are presented in Table 6.

The first cluster (#0) is named 'biology education' and includes the items 'scientific knowledge' and 'content knowledge and teaching biology'. The studies in the former item include subdisciplines of biology. In the latter items, the studies examine the teacher's subject content knowledge (SCK) and pedagogical content knowledge (PCK). The items in 'outlier' are Arita's (2017), Livotov et al.'s (2021), Pessoa et al.'s (2024), and Santhosh et al.'s (2025) studies. They are excluded from the following content analysis because the first three focus on topics outside biology education, and the last one was published outside the time range of this study.

The second cluster (#1) is named 'sustainability, sustainable education (SE), and sustainable education goals (SDGs)'. The items include studies that examine, e.g., how sustainability and sustainable development goals (SDGs) are related in science education, including biology education. The item 'outlier' is the study of Stevens et al. (2022), which describes teaching and learning of life's principles in Biomimicry Design Thinking Courses. Because the study does not refer to teacher education or school education, it has been excluded from the following content analysis.

The third cluster (#2) is named 'teacher education and school education' and includes studies concerning ideas of sustainability and environmental sustainability in relation to prospective learning. The items in 'outlier' are the studies of Hawa et al. (2021) and Wright et al. (2008). Because these studies do not refer to teacher education or school education in biology, they have been excluded from the following content analysis.

The fourth cluster (#3) is named 'holistic view of sustainability education' and includes the items 'inter- and transdisciplinarity' and 'transformative education'. The item 'outlier' is the study of Medir et al. (2016), which examines non-formal environmental education evaluation. Because the study does not refer to teacher education or school education in biology, it has been excluded from the following content analysis.

The fifth cluster (#4) is named 'learning and teaching methods in biology education' and includes studies concerning information and communication technology (ICT), problem-based learning (PBL), field work and experiential learning, problem-solving, project-based learning (PjBL), inquiry-based learning, game education, role-playing, and flipped classroom.

The sixth cluster (#5) is named 'sustainability competencies and skills' and includes studies concerning teacher education in sustainability, sustainability curricula, sustainability policy, and research and teaching gaps. The item 'outlier' is the study of Paulauskaite-Taraseviciene et al. (2022) about engineering education. Because it does not refer to biology education, it has been excluded from the following content analysis.

4.2.2. Content Analysis

The bibliometric technique predominantly offers quantitative insights and does not facilitate a comprehensive examination of the specific content or context of individual studies. Therefore, to gain a more detailed understanding of the implementation of SE across different educational views on biology education focused on sustainable development, qualitative systematic reviews were carried out from the clustered material (n = 165). Based on manual checking, 34 studies were rejected because one was published outside the time range of this study, and the rest were not focused on biology teacher education or

school teaching in biology (see Appendix A). This process resulted in a refined selection of 131 studies directly related to teaching and learning in science education and particularly in biology education. The studies examined biology teaching at different educational levels in 43 countries (Table 7). The largest number of studies concerned university teaching (n = 106) and the smallest number primary level teaching (n = 18). From all university studies, the majority concerned biology teaching in USA (n = 33). The remaining studies were fairly evenly distributed across the world.

Table 7. The countries and educational levels of the studies.

Countries	**Studies in Educational Levels (n)**		
	Primary	**Secondary**	**University**
Albania		1	
Australia	1	2	5
Austria			1
Brasília			2
Canada			2
China			1
Greece	1	1	
Croatia	1		
Cyprus		1	
Denmark			1
Dubai			1
Finland	2	2	2
Germany	2	6	6
Greece			1
Indonesia		2	6
India	1	1	2
Ireland	1	1	1
Israel		2	6
Italy		1	1
Malaysia	1	2	4
Mexico		1	
The Netherlands			1
New Zealand	1	1	1
Nigeria			1
Norway	1	1	1
Oman			1
Pakistan			1
Portugal	2	2	1
Rwanda			1
Saudi Arabia			1
Slovenia			1
Spain	1	5	5
Sweden		2	1
Switzerland		2	1
Taiwan		1	
Thailand			1
Turkey	1	2	2
UK	1	5	8
Ukraine			2
Uruguay		1	
USA	1	7	33
Uzbekistan		1	
Vietnam			1
Total (n)	**18**	**52**	**106**

The studies were analyzed following the method of content analysis (Elo & Kyngäs, 2008). Content analysis is a well-established research technique that systematically focuses on the content of studies. The approach involves an examination of the objectives, key findings, and implications of each study, keeping the research questions in mind, to identify recurring themes related to SE in biology education. The themes are summarized and organized in a tabular format.

In this study, the retrieved data were analyzed qualitatively to map pedagogical innovations and conceptual linkages among the core sustainability elements. A deductive content analysis (Elo & Kyngäs, 2008) was used as the only analysis method to determine SDGs, learning objectives, and subject matter content knowledge (SCK) in biology education. It was also used in the first analysis phase to determine teaching and learning methods and competencies and skills. In the second analysis phase, the inductive content analysis method (Elo & Kyngäs, 2008) was used to determineteaching and learning methods and competencies and skills. Inductive content analysis was used as the only method to determine the subject aims, pedagogical content knowledge (PCK), and assessment methods. In the deductive analyses, the used criteria are described in the Findings section.

The generalizability of the findings relates to the selection of the analyzed data. Researcher triangulation was a part of the analysis process. To ensure that the categorization decisions were based on comprehensive understanding of the studies, one researcher carefully read all the articles thrice, and another researcher also familiarized himself with the entire material. Thereafter, in order to ensure the reliability of the process, the researchers checked the selections together. As such, decisions always include elements of subjective interpretation. Thus, joint discussions between the researchers concerning the studies are essential. Therefore, the valid findings and the conflicting views of the analysts were addressed. The discussion continued until clear arguments were found and a consensus was reached on points to be deleted or added. Based on the discussions, the researchers made the selections together. This ensured that decisions were not based on the first impression of one person's studies but on reasoned joint discussions. Thus, the analysis is based on what the authors of the articles have explicitly written and not on what the authors of this study could read between the lines as the researchers' intentions. Because inter-rater reliability is the degree of agreement among independent observers who rate, code, or assess the same phenomenon (Saal et al., 1980), there was no need to calculate inter-rater reliability in this study due to the dialogical nature of the analysis.

The study is conducted respecting the general ethical principles presented in Finnish National Board on Research Integrity TENK guidelines. TENK (2019, p. 22) states that no ethical review statement from a human sciences ethics committee is needed when the research is based only on public information, archive data, or registry and documentary data without the data security risks associated with data that is combined from several resources.

5. Findings

Teaching aims and learning objectives guide and influence all kinds of teaching and learning in the cognitive, affective, and psychomotor domains (cf. Bloom et al., 1956). Traditional biology teaching is deductive and involves the principles and methods used by teachers. In this teacher-centered learning approach, teachers are the authorities and students are the recipients of information-giving lectures or presentations. Learning is often measured using objectively scored tests and assessments. Alternative teaching methods are inductive. According to Prince and Felder (2006), inductive teaching and learning is an umbrella term that encompasses a range of instructional methods, including, e.g., inquiry learning, problem-based learning, project-based learning, case-based teaching, discovery learning, and just-in-time teaching. In this student-centered learning approach, teachers

and students play equally active roles in the learning process. During their studies, students discuss issues together (cooperative and collaborative learning) and solve problems (active learning) inside or outside the classroom. Learning is continuously measured using both formal and informal forms of assessment, including, e.g., group projects, student portfolios, and class participation (Prince & Felder, 2006).

5.1. Sustainable Development Goals (RQ 1)

To determine the SDGs included in biology education, the mentions in the reviewed studies are collected and classified using a deductive content analysis (Elo & Kyngäs, 2008) based on the UNESCO's (2017a) definitions.

In total, there are 133 mentions of SDGs. The most mentioned dimensions of SDGs are social and environmental dimensions (n = 58 and 52, respectively) (Figure 6). Relatively little reflection concerns the economic and institutional dimensions (n = 12 and 11, respectively). Out of the single SDGs, quality education (SDG 4) is the one mentioned most often (n = 16). By contrast, decent work and economic growth (SDG 8) and industry, innovation, and infrastructure (SDG 9) are reflected only rarely (n = 4 and 3, respectively).

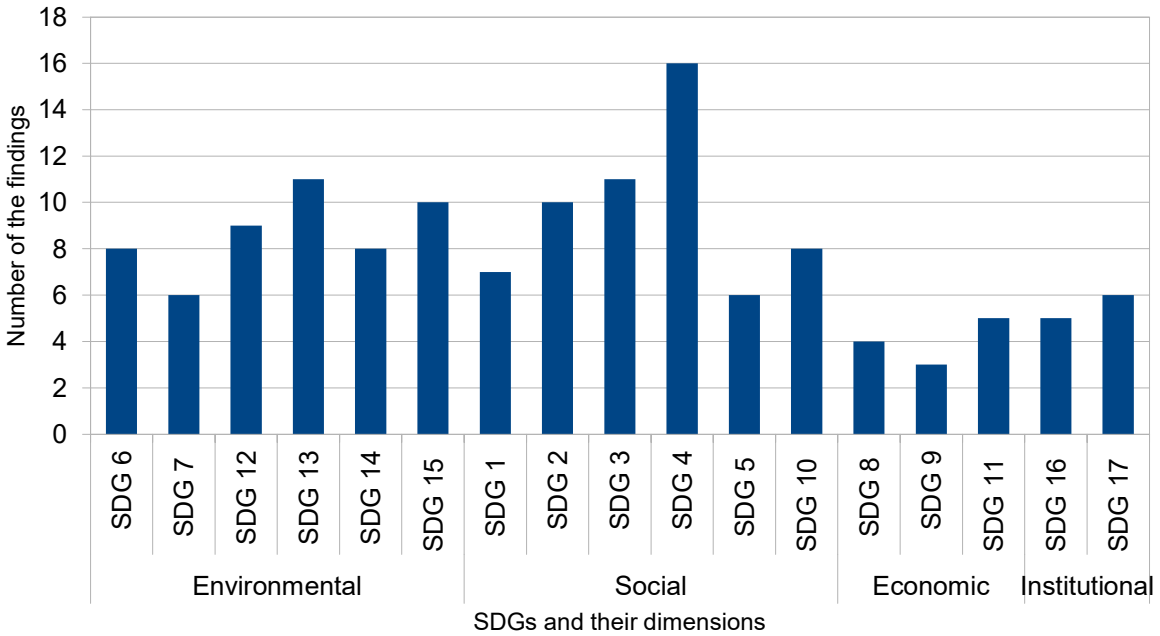


Figure 6. The sustainable development goals (SDGs) and their dimensions included in biology education promoting sustainable development based on deductive content analysis (Elo & Kyngäs, 2008) according to UNESCO (2017b). The total number of the reviewed studies is 131.

The findings suggest that quality education (SDG4) and the integration of SDG knowledge are important in biology education. Many of the SDGs are directly related to biological subject content (e.g., ecology, evolution, and biodiversity) (cf. Dempster, 2023) and to science education regarding Visions II and III. By integrating sustainable development dimensions into biology teaching and learning, educators can promote, for example, students' understanding of the structure, function, evolution, and biodiversity of ecological systems.

5.2. Competencies and Skills Promoting Sustainable Development in Biology Education (RQ 2)

To determine the competencies and skills promoting sustainable development in biology education, the mentions in the reviewed studies are collected and classified first using a deductive content analysis (Elo & Kyngäs, 2008) based on Wiek and Redman (2022)

and Sposab and Rieckmann (2024), and thereafter using an inductive content analysis (Elo & Kyngäs, 2008).

The most mentioned competencies and skills are critical thinking and reflection (n = 30 and 28, respectively) (Figure 7). These are followed by problem-solving and values-thinking (n = 26 and 24, respectively). Also, communication, collaborative decision-making, and interdisciplinary work are mentioned frequently (n = 20, 20, and 18, respectively). Strategic thinking and empathy are the least mentioned (n = 6 and 9, respectively).

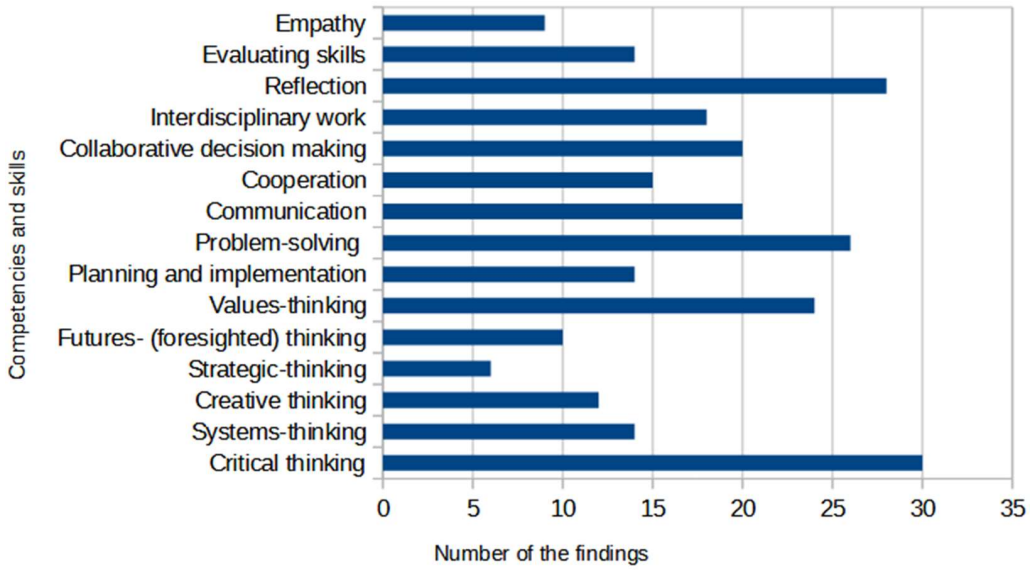


Figure 7. Competencies and skills in biology education promoting sustainable development based on deductive content analysis (Elo & Kyngäs, 2008) according to Sposab and Rieckmann (2024), UNESCO (2017a), and Wiek and Redman (2022). The total number of the reviewed studies is 131.

In addition to the competencies and skills mentioned in Figure 7, using an inductive content analysis, two mentions of integrated problem-solving competency are found in the analyzed studies.

The findings suggest that critical thinking, reflection, problem-solving, and values-thinking are important competencies and skills for promoting sustainable development. For example, critical thinking for action in biology teaching involves, among other things, engaging students in decision-making and developing appropriate behavior in controversial issues (Puig & Jiménez-Aleixandre, 2022), while values-thinking promotes a commitment to equality and justice (Persano Adorno et al., 2025). By emphasizing these competencies, educators can awaken a sense of agency and responsibility in their students and empower them to promote meaningful change.

5.3. Subject Aims and Learning Objectives Promoting Sustainable Development in Biology Education (RQ 3)

5.3.1. Subject Aims

To determine the subject aims in biology education promoting sustainable development, the mentions in the reviewed studies are collected and classified using an inductive content analysis (Elo & Kyngäs, 2008).

In total, there are 251 mentions of subject aims. The most frequently mentioned ones are the development of students' conceptual knowledge and factual knowledge (n = 52 and 51, respectively) (Figure 8). The subject aims related to the development of scientific skills, environmental awareness, emotions and attitudes, and the ability to apply knowledge in different situations also have many mentions, but clearly fewer than the first two. The least

frequently mentioned subject aim is the development of students' attitudes towards science and science learning (n = 21).

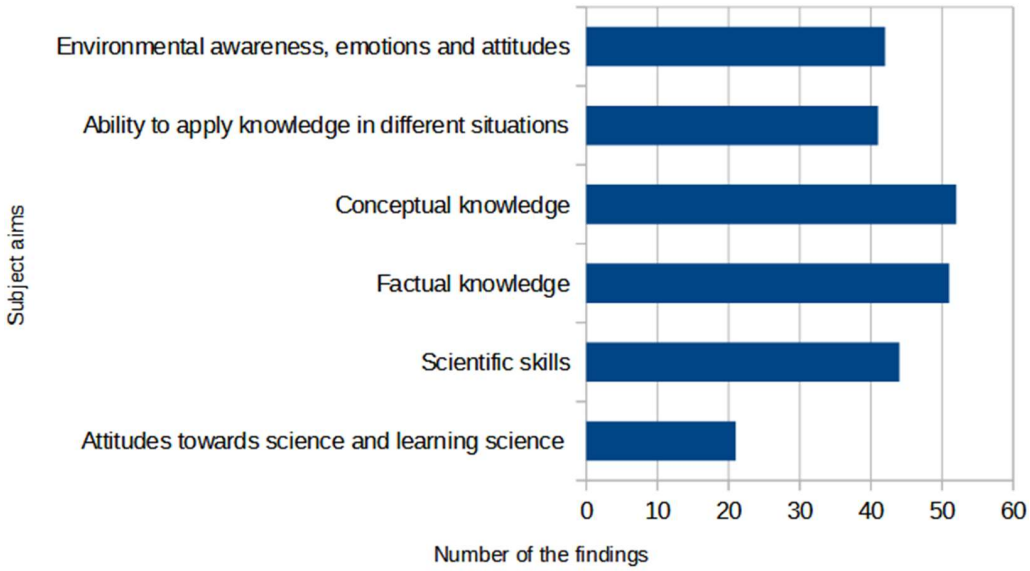


Figure 8. Subject aims in biology education promoting sustainable development based on inductive content analysis (Elo & Kyngäs, 2008). The total number of the reviewed studies is 131.

The findings suggest that the development of factual and conceptual knowledge is at the core of the subject aims, as also stated in the study by Erduran and Dagher (2014). Educators should place more emphasis on scientific skills (Dogan & Kunt, 2017), environmental awareness and emotions (Ballard et al., 2024; Gazoulis et al., 2022), and attitudes (Kahveci, 2023), as well as on the ability to apply acquired knowledge in real-life situations, to increase students' understanding of living systems and the relationships between humans and nature.

5.3.2. Learning Objectives

To determine learning objectives promoting sustainable development in biology education, the mentions in the reviewed studies are collected and classified using a deductive content analysis (Elo & Kyngäs, 2008) based on the taxonomy of learning objectives (Bloom et al., 1956; Krathwohl, 2002).

Bloom et al. (1956) identified three domains of learning objectives: cognitive (intellectual), affective (emotional), and psychomotor (behavioral). *Cognitive learning* involves the acquisition of factual knowledge and the development of intellectual skills, abilities, and thought processes (thinking skills). *Affective learning* involves the ways in which people emotionally process information and stimuli. Emotional learning and development are essential to the construction of the learner's feelings, values, and motives, and are at the foundation of one's receptivity to information. Finally, *psychomotor learning* involves behavior and activity connected with one's perceptual responses to inputs, to the activity of imitation (modeling and vicarious learning), and to the manipulation of one's environment (instrumental learning). Krathwohl revised Bloom's taxonomy in 2002. The revised taxonomy is a hierarchy in the sense that the six major categories of the cognitive process dimension are believed to differ in their complexity, with the remember category being less complex than the understand category, which is less complex than the apply category, and so on (Table 8).

In total, there are 608 mentions of the learning objectives in the studies reviewed. The most frequently mentioned learning objectives are related to cognitive learning (n = 509)

(Figure 9). By contrast, there is weak coverage of psychomotor and affective learning (n = 67 and 32, respectively). From the single learning subdimensions, factual knowledge (facts) is mentioned the most often (n = 103). Remember and understand are also often stated (n = 91 and 70, respectively). Instrumental learning and vicarious learning (n = 33 and 34, respectively) are rare, and create is very rarely mentioned (n = 25).

Table 8. The cognitive process dimensions of the revised taxonomy (Krathwohl, 2002).

Criteria	Cognitive Process Dimensions
Retrieving relevant knowledge from long-term memory	Remember
Determining the meaning of instructional messages, including oral, written, and graphic communication	Understand
Carrying out or using a procedure in a given situation	Apply
Breaking material into its constituent parts and detecting how the parts relate to one another and to an overall structure or purpose	Analyse
Making judgments based on criteria and standards	Evaluate
Putting elements together to form a novel, coherent whole or make an original product	Create

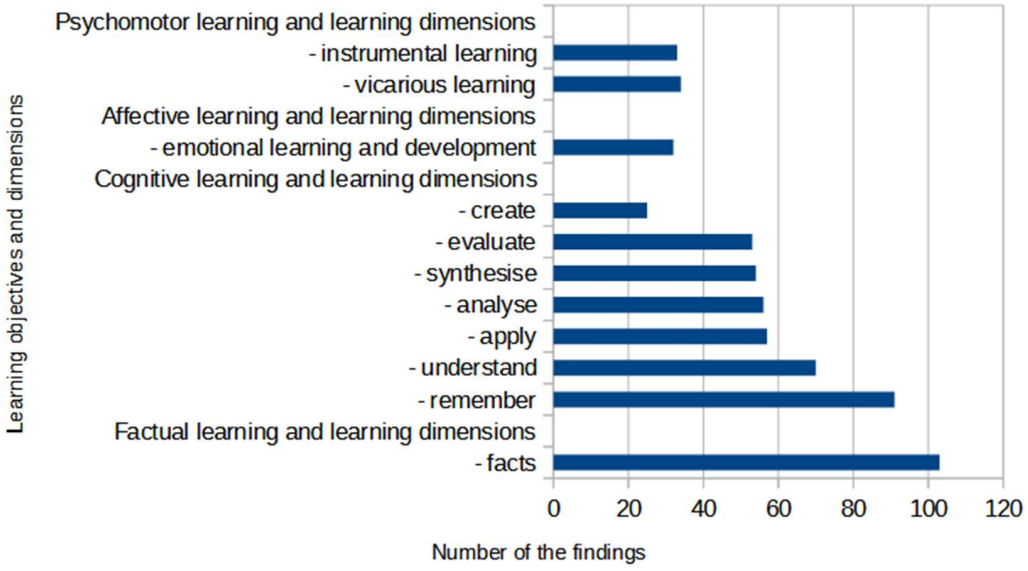


Figure 9. Learning objectives and dimensions in biology education promoting sustainable development collected and classified based on deductive content analysis (Elo & Kyngäs, 2008) according to Bloom et al. (1956) and Krathwohl (2002). The total number of the reviewed studies is 131.

The findings suggest that, in addition to factual and cognitive learning objectives, affective and psychomotor learning objectives are considered to be important in biology education. By integrating these learning objectives in biology education, educators can support students to take responsibility for their decisions and actions, and to be aware of their impact on sustainable development.

5.4. Content Knowledge Promoting Sustainable Development in Biology Education (RQ 4)

To determine the levels of *subject matter content knowledge* (*SCK*) promoting sustainable development, the mentions in the reviewed studies are collected and classified using a de-

ductive content analysis (Elo & Kyngäs, 2008) based on Bloom's new taxonomy (Krathwohl, 2002) according to Aksela et al. (2012) (Table 9). In this analysis, the next knowledge level always includes the previous one/the previous ones; e.g., concept knowledge includes fact knowledge, and method knowledge includes both fact and concept knowledge, etc.

Table 9. The new taxonomy of Bloom (Krathwohl, 2002) according to Aksela et al. (2012).

Criteria	Knowledge Level
Terminology of biology	Factual (fact) knowledge
Classification of biological knowledge; theories, models, structures	Conceptual (concept) knowledge
Problem solving, research methods and techniques	Methodological (procedural) knowledge
Making summaries, self-knowledge	Metacognitive knowledge

In addition, the levels of thinking skills achieved during the learning processes are analyzed using the verbs defined by Stanny (2016) (Table 10). These verbs are applied as background information to support interpretation if the taxonomy level is not clearly stated in the study or is not represented in verb form.

Table 10. Bloom's taxonomy verbs used to support the analysis (Stanny, 2016).

Knowledge	Understand	Apply	Analyze	Evaluate	Create
Arrange	Articulate	Act	Analyze	Appraise	Arrange
Choose	Associate	Adapt	Appraise	Argue	Assemble
Cite	Characterizise	Apply	Break	Arrange	Categorize
Copy	Cite	Back/back up	Break down	Assess	Choose
Define	Clarify	Calculate	Calculate	Attach	Collect
Describe	Classify	Change	Categorize	Choose	Combine
Draw	Compare	Choose	Classify	Compare	Compile
Duplicate	Contrast	Classify	Compare	Conclude	Compose
Identify	Convert	Complete	Conclude	Contrast	Construct
Indicate	Defend	Compute	Contrast	Core	Create
Label	Demonstrate	Construct	Correlate	Counsel	Design
List	Describe	Demonstrate	Criticize	Create	Develop
Locate	Differentiate	Develop	Debate	Criticize	Devise
Match	Discuss	Discover	Deduce	Critique	Estimate
Memorize	Distinguish	Dramatize	Detect	Decide	Evaluate
Name	Estimate	Employ	Diagnose	Defend	Explain
Order	Explain	Experiment	Diagram	Describe	Facilitate
Outline	Express	Explain	Differentiate	Design	Formulate
Quote	Extend	Generalize	Discover	Determine	Generalize
Read	Extrapolate	Identify	Disseminate	Discriminate	Generate
Recall	Generalize	Illustrate	Dissect	Estimate	Hypothesize
Recite	Give	Implement	Distinguish	Evaluate	Inprove
Recognize	Give examples	Interpret	Devide	Explain	Integrate
Record	Identify	Interview	Evaluate	Grade	Invent
Relate	Illustrate	Manipulate	Examine	Invent	Make
Repeat	Indicate	Modify	Experiment	Judge	Manage
Reproduce	Infer	Operate	Figure	Manage	Modify
Review	Interpolate	Organize	Group	Mediate	Organize
Select	Interpret	Paint	Identify	Prepare	Originate
State	Locate	Practice	Illustrate	Probe	Plan
Tabulate	Match	Predict	Infer	Rate	Predict
Tell	Observe	Prepare	Inspect	Rearrange	Prepare
Underline	Organize	Produce	Inventory	Reconcile	Produce

In total, there are 316 mentions of the levels of SCK. Factual and conceptual knowledge (n = 107 and 103, respectively) are the most frequently mentioned levels (Figure 10). Methodological knowledge and metacognitive knowledge (n = 61 and 45, respectively) are reflected less often.

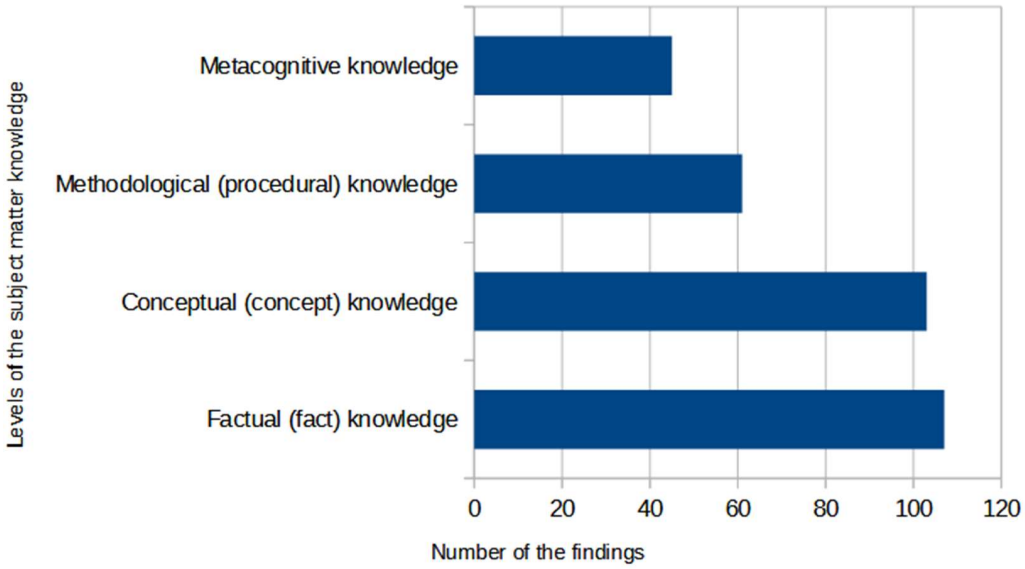


Figure 10. Levels of the subject matter knowledge (SCK) in biology education promoting sustainable development based on deductive content analysis (Elo & Kyngäs, 2008) according to Aksela et al. (2012). The total number of the reviewed studies is 131.

Powerful knowledge and pedagogical content knowledge (*PCK*) included in biology education promoting sustainable development mentioned in the reviewed studies are collected and classified using an inductive content analysis (Elo & Kyngäs, 2008). The former is explicitly mentioned three times and the latter ten times.

The findings show that biology education currently emphasizes acquiring factual and conceptual knowledge more than other knowledge types. To support students in developing a more holistic perspective, educators could use methods where students can examine their own or others' thinking, knowledge, or actions, for example, regarding food production, climate change, biodiversity, or ecosystem services (Jensen, 2025).

5.5. Teaching and Learning Methods Promoting Sustainable Development in Biology Education (RQ 5)

To determine the teaching and learning methods promoting sustainable development in biology education, the mentions in the reviewed studies are collected and classified first using a deductive content analysis (Elo & Kyngäs, 2008) based on Ghafar (2023), Kesler (2020), Landøy et al. (2020), Södervik (2024), and Yli-Panula et al. (2018), and thereafter using an inductive content analysis (Elo & Kyngäs, 2008).

In total, there are 446 mentions about teaching and learning methods in the analyzed studies. The findings of the deductive content analysis are shown in Figure 11a, and the findings of the inductive content analysis in Figure 11b.

Based on the findings, the most popular teaching and learning methods are interactive methods (n = 285), followed by student-centered methods (n = 117), and then teacher-centered methods (n = 44). Out of single teaching and learning methods, discussion (n = 33), problem-solving learning (n = 32), and cooperative and collaborative learning (n = 32) are the most mentioned ones. These are followed by problem-based learning (n = 26), inquiry-based learning (n = 23), and project-based learning (n = 22). Lecture-based methods, experiential learning, and place-based and community-based education are also

mentioned often (n = 20, 19, and 17, respectively). ICT with different applications (virtual learning, simulations, and animations) is mentioned quite often, with the exception of artificial intelligence (AI). AI is one of the least mentioned teaching and learning methods (n = 1). Others are brainstorming, participatory action research, life-cycle analyses (all n = 2), fore- and backcasting methods, and whole-school approach (both n = 1).

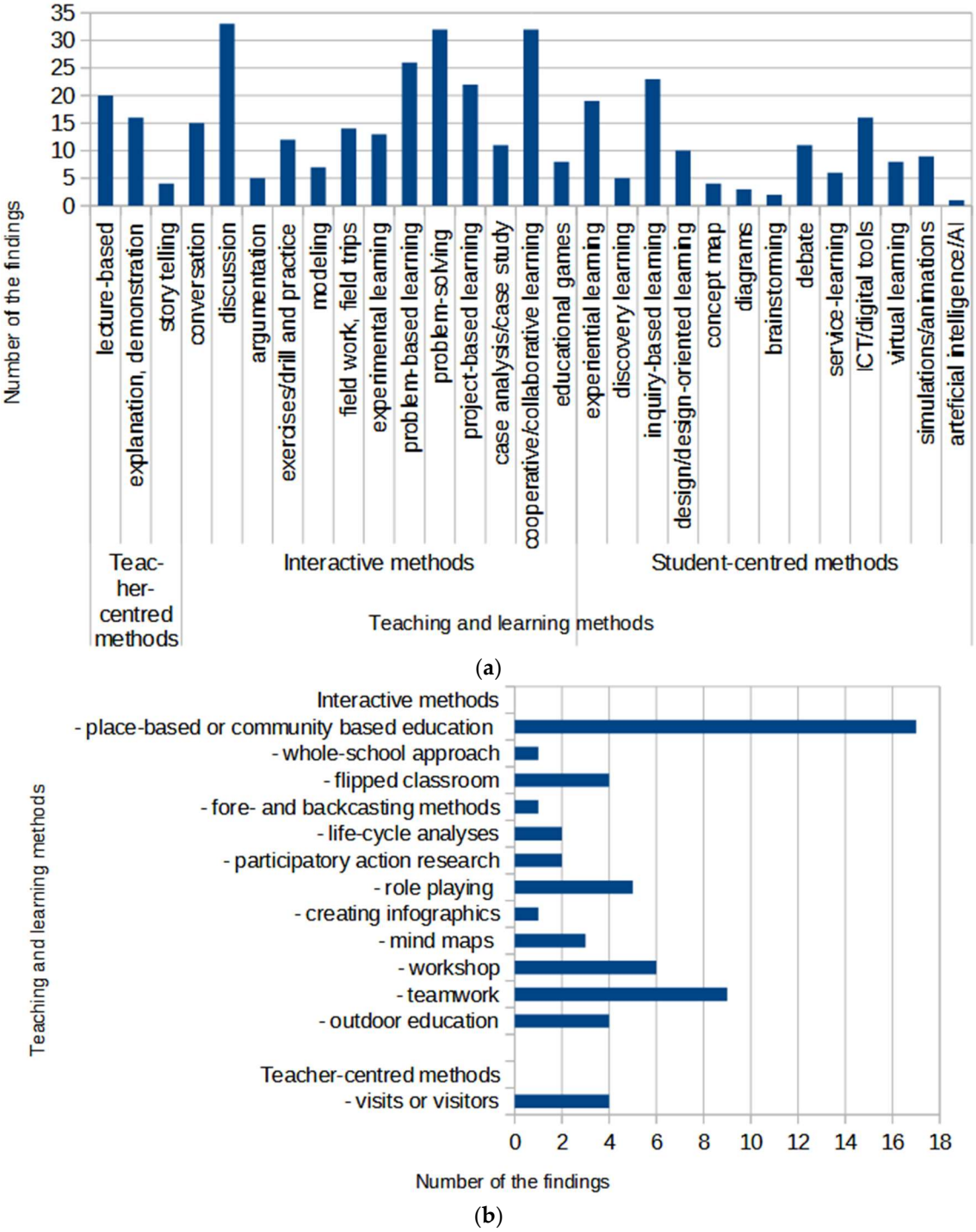


Figure 11. (**a**). Teaching and learning methods in biology education promoting sustainable development based on deductive content analysis (Elo & Kyngäs, 2008) according to Ghafar (2023), Kesler (2020), Landøy et al. (2020), Södervik (2024), and Yli-Panula et al. (2018). The total number of the reviewed studies is 131. (**b**). Teaching and learning methods in biology education promoting sustainable development based on inductive content analysis (Elo & Kyngäs, 2008). The total number of the reviewed studies is 131.

Based on the findings, the most popular teaching and learning methods are research-based and promote student participation and agency. When they are used, a transformative pedagogical perspective is also realized (E. Jeronen et al., 2022). In addition, argumentative work methods that emphasize emotional skills and value and attitude education are suitable for sustainability education (Yli-Panula et al., 2018). For example, the use of argumentation exercises required for ethical reasoning regarding ecosystem services can promote new perspectives on the well-being of nature and people. To help students develop an integrative approach to biological phenomena, educators should use student-activating and teaching approaches contextualized to real-life situations to arouse students' desire to explore their own and others' thinking, information, knowledge, and actions.

5.6. Assessment Methods and Types of Measurement Tasks Promoting Sustainable Development in Biology Education (RQ 6)

Assessment supports the work of teachers and students and serves as a tool for the development of teaching and learning. Timely and effective feedback allows educators to adapt their teaching to the learning needs of the students, which can improve students' motivation and learning outcomes (Merchant et al., 2014).

To determine different assessment methods and types of measurement tasks promoting sustainable development included in biology education, the mentions in the reviewed studies are collected and classified using an inductive content analysis (Elo & Kyngäs, 2008).

Based on the findings, assessment methods of sustainable development in biology education are not studied very often. In total, there are 49 mentions concerning assessment methods. Summative and formative methods are used quite often, but diagnostic methods only very rarely (n = 25, 21, and 7, respectively). In summative assessment, tests and exams are often mentioned. Also, the assessments of different kinds of student products are popular (self-tests, essays, project reports, portfolios, and practical works). In addition, peer-based grading and retrospective discussion are used. In formative assessment, in addition to the teacher's continuous feedback, peer review and the student's self-assessment are used. In diagnostic assessment, tests and self-reports are the only mentioned assessment types.

The findings show that relatively little attention is currently paid to assessment in biology education. Moreover, there is an overemphasis on summative and formative methods relative to diagnostic methods. Thus, the previous knowledge of students is currently not accounted for when selecting the content knowledge for teaching and learning. Using various assessment methods, educators could develop their teaching processes and the curriculum (Lyon, 2013).

6. Discussion

The integration of sustainable development into biology education is a growing area of interest. A holistic view of the educational processes is needed for understanding all the educational effects. This study explores recent research findings on didactic approaches of biology education from a sustainable development perspective in teacher education and primary and secondary school education. For a systematic review, documents were identified using bibliometric analysis and deductive and inductive content analyses. The study offers insights to improve pedagogical and didactic approaches in biology education for promoting sustainable development.

As for the trustworthiness of the study (Elo et al., 2014), the design and implementation of the study were negotiated among the researchers throughout the research process. Searches of data were carried out with numerous keyword combinations. The study procedures were carefully documented to review and verify data throughout the study. The analysis of the data was carried out by using inductive and deductive analyses. The

findings were validated through joint discussions of the researchers. The results were also compared with previous studies.

However, all teaching and learning situations are context- and topic-specific, and therefore, when selecting and applying teaching approaches, cultural as well as current phenomena and issues need to be taken into account.

The findings highlight some challenges to adopting active student-centered pedagogical and didactic approaches in the integration of sustainable education (SE) in biology education. They should be discussed from the perspective of the development of biology education promoting sustainable development to support the shift towards sustainable living and well-being.

6.1. Sustainable Development Goals

With the in-depth promotion of the United Nations Sustainable Development Goals (SDGs), biology education plays a crucial role in the global education system for fostering students with environmental awareness, ecological ethics, and social responsibility. In total, there are 133 mentions of SDGs across the 131 studies reviewed. As in Yli-Panula et al.'s (2020a) study, the most often expressed dimensions of sustainable development in this study are the environmental and social ones, while the economic and institutional dimensions are seldom reflected.

Many of the SDGs are directly related to biological subject content (e.g., ecology, evolution, and biodiversity) (cf. Dempster, 2023) and to science education regarding Visions II and III. Overall, this study concludes that biology education must still evolve beyond content mastery to integrate ethical, technological, and transdisciplinary dimensions—empowering learners not only to understand life but to sustain it, aligned with quality education (SDG 4), good health and well-being (SDG 3), and life on land (SDG 15).

Out of the single SDGs, quality education (SDG 4) is the most reflected. SDG 4 has also generated much debate around the world today (e.g., Efe & Umdu Topsakal, 2025; Villarosa, 2025; Ölçer-Çevik & Kozaner, 2025). The reason is that the UN General Assembly Resolution 74/233 (UN, 2019) reinforced education for sustainable development (ESD) as an essential part of Sustainable Development Goal 4 on education and a key enabler of all the other sustainable development goals by calling on countries to strengthen implementation. SDG 4 is crucial as it provides the foundation for all the other sustainable development goals for training professionals with a global perspective and social and economic responsibility (Espinosa-Gutirrez et al., 2025).

The other SDGs are clearly less reflected than SDG 4. This finding is in line with the research of Yli-Panula et al. (2020a, 2020b). It indicates that ethical, technological, and interdisciplinary dimensions should be integrated into biology teaching more broadly, especially in terms of good health and well-being (SDG 3) and life on land (SDG 15). This would help to develop students' ability to understand and sustain life.

Aligning biology education with SDGs may provide a structured framework for addressing global challenges, such as climate change, biodiversity loss, and inequality. This integration may support students' understanding of the broader implications of their studies and their own role in achieving these goals. They emphasize the dimensions that should be accounted for in order to genuinely overcome the problems that affect humanity and the environment over the years. The SDGs address the global ecological crisis for preserving the environment and promoting social development, as well as how to educate a new generation of biology professionals with a global perspective and a strong sense of social and economic responsibility.

By integrating sustainable development dimensions into biology teaching and learning, educators can promote, for example, students' understanding of the structure, function, evolution, and biodiversity of ecological, social, and economic systems.

However, many scholars have criticized SDGs. They have stated that SDG 4 prepares students to preserve the status quo. Instead, the goal should be to empower students to challenge both their personal and socially established norms, values, ethical, and political views. Students also require knowledge about options for action in order to be prepared to act. Action knowledge should enable effective choices when weighing the potential consequences of different possible actions. Students require the ability to imagine possible future situations in which a particular course of action is taken or not taken. Spaiser et al. (2016) have pointed out that the SDGs are inconsistent, especially between environmental sustainability and socio-economic development. They also argue that SDGs are not binding, and each country is expected to develop its own national or regional plans. Furthermore, the source(s) and scale of the financial resources and investments required to achieve the SDGs are unclear (Swain, 2018).

6.2. Competencies and Skills Promoting Sustainable Development

In total, there are 260 mentions of competencies and skills promoting sustainable development in this study. The most frequently mentioned competencies and skills are critical thinking and reflection, followed by problem-solving and values-thinking. Also, communication, collaborative decision-making, and interdisciplinary work are mentioned quite often. Strategic thinking and empathy are the least mentioned ones. The following sections discuss the competencies and skills that are commonly mentioned in biology education, starting with those most frequently mentioned.

As in the study by Caeiro and Simão (2025), the most frequently mentioned competency in this study is critical thinking. *Critical thinking* is key for understanding different scientific issues and perspectives of stakeholders. It involves, among other things, engaging students in decision-making and developing appropriate behavior regarding controversial issues (Puig & Jiménez-Aleixandre, 2022). The importance of critical thinking for creating a better future has been discussed since the early days of sustainable development (cf. Elkington, 1998/2007; Kumar & Kumar Choudhary, 2025). Through critical thinking, environmental issues can be deeply analyzed with an objective and evidence-based approach, and it becomes possible to make wise decisions in the face of ecological challenges (van de Wetering et al., 2022).

In the analyzed studies, it has been seen that an important part of biology teaching is the students' *reflection* on their own action and its consequences based on their experiences. The findings support previous studies, which showed that reflection has a meaningful role in acquiring the knowledge and skills needed to solve the complex challenges of sustainable development (Colomer et al., 2020; Whalen & Paez, 2021). According to Zhou et al. (2025), the acquired knowledge, values, and attitudes have implications for the perception of sustainability and finding solutions to problems. They also affect cooperation and a sense of responsibility, as well as the ability to solve complex problems.

Problem-solving and *value thinking* are also mentioned quite often. The findings support the idea that these skills are seen as important for achieving the sustainable development transition (Kesler et al., 2024) because the rapid development of science generates technologies that increasingly affect people's lives and raise increasingly complex moral and ethical questions (Chowdhury, 2016). Practicing creative problem-solving may foster students' creative thinking to develop innovations in their own living environments (Fatmawati, 2020). Value thinking is needed for knowing how to define, compare, apply, reconcile, and discuss the values, principles, and goals of sustainability, for example, from the perspective of

justice, equity, and responsibility in various processes, including visioning and evaluation (Wiek et al., 2016).

The design and implementation of educational processes must take into account the conditions in which both rational and emotional relationships can be created between the student and the moral object (Zeidler et al., 2019). Many themes of sustainable development, such as human rights, animal rights, and natural values, are value-based, and they are also included in biology education. Values are mentioned separately in Vision I, but they are also included in Vision II and Vision III. Vision II emphasizes contextual learning and the application of knowledge and skills in the individual's own life situations and as a member of their community, and Vision III emphasizes critical thinking skills, reflection, and value thinking to promote sustainable development (Uitto et al., 2024a). Value thinking is important, especially for promoting commitment to equality and justice (Persano Adorno et al., 2025).

Systems thinking, *strategic–thinking*, and *futures-thinking* are mentioned rarely in the studies reviewed. This finding indicates the need to add the development of these thinking skills into schoolwork. Systems thinking, strategic thinking, and futures-thinking are important in biology teaching and learning because biology includes the understanding of concepts and their mutual relationships. For example, the concept photosynthesis is related to climate change and, through evolutionary mechanisms, to biodiversity and habitat loss (Palmberg et al., 2017). Biology teaching and learning also include various local, regional, and global sustainability issues. When students are able to analyze these, they master systemic thinking (Wiek et al., 2016). Students possess strategic thinking when they know how to develop and test interventions and transition strategies that promote sustainable development, taking into account undesired consequences and their ramifications. They master futures-thinking when they know how to foresee problems of sustainability, create and form sustainable and desirable visions of the future, and examine alternative development paths in the light of evidence. In an increasingly complex world, systems thinking, strategic thinking, and futures-thinking are basic skills for every citizen. Sustainability cannot be understood without them (cf. Gilissen et al., 2020).

The findings of this study match Yli-Panula et al.'s (2020a, 2020b) in that biology education is seen as important in developing students' sustainability competence. However, *integrated problem-solving* is mentioned only twice in the analyzed studies. It should be emphasized more because it is crucial in transformative teaching and learning for sustainable development (Sjöström & Eilks, 2018; Valladares, 2021). In a rapidly changing world, citizens should be able to critically evaluate scientific information and base their decisions on scientific information both in their private lives and in their professional and social activities.

Empathy is one of the least mentioned competencies. However, it is important for understanding one's own relationship with other people as well as the relationship between humans and nature. It may also support students' continuous self-development, responsible action, and active participation in the development and implementation of sustainable practices, and in preparing for the future.

Cognitive, affective, and functional competencies are all important for promoting sustainability according to international competence frameworks for sustainability education (UNESCO, 2017a, 2017b; Bianchi et al., 2022).

By emphasizing these competencies, educators can awaken a sense of agency and responsibility in their students and empower them to promote meaningful change.

Shephard (2022) questions the role of competence concerning SE. He argues that the definitions of competence that are widely used in SE confuse cognitive and affective goals related to the ability to do something and the willingness to do the same thing in a way that

is not useful in teaching and learning environments. According to Shephard, teaching the ability to act in accordance with sustainable development and teaching the same student the willingness to behave in a sustainable way are different teaching tasks, which require different teaching and learning methods, different assessments, and perhaps even different teachers. Therefore, according to Shephard, the term "competent" should be replaced by the terms "able" and "willing". A change in terminology would allow for more effective communication about sustainability issues than is currently the case.

6.3. Subject Aims and Learning Objectives

6.3.1. Subject Aims

The subset of curricular subject matter that the teacher considers to be the most important for the students to learn plays a crucial role when teachers plan the subject aims for their teaching, for a student's individual learning, and for the whole of the students' learning process. In total, there are 251 mentions of subject aims in this study.

The most frequently mentioned subject aims in the analyzed studies are to develop students' factual and conceptual knowledge. The subject aims regarding the development of scientific skills, environmental attitudes, environmental awareness, and feelings are mentioned less frequently than the aims of factual and conceptual knowledge. The attitude aims regarding natural sciences and learning natural sciences receive very few mentions.

The emphasis of the subject aims on factual and conceptual knowledge aims is important for recognizing the ecosystem's crucial meaning for human life and for global sustainable development. However, this may lead to insufficient implementation of teaching in accordance with the nature of science (NOS) (Erduran & Dagher, 2014), as stated in the previous studies of teaching practices (Hiltunen et al., 2021) and textbooks (Su et al., 2025). In order for teaching to be implemented in accordance with the NOS, more attention should be paid, in addition to factual and conceptual knowledge, to the types of scientific skills needed to protect the ecological environment.

Scientific skills are important to define in subject aims because education and experiences influence students' attitudes and values and shape their behavior (Bandura, 1977). There are two types of scientific skills. General scientific skills concern scientific thinking and knowledge generation by using scientific processes (Dogan & Kunt, 2017). Scientific process skills, on the other hand, are skills that facilitate learning in science, provide the means for research and active learning, develop a person's sense of responsibility during learning, and increase the retention of knowledge (Dogan & Kunt, 2017).

Scientific skills are needed to enhance the participation and empowerment of students (Yli-Panula et al., 2022a). Through scientific skills, students may recognize, e.g., the importance of biodiversity and climate change and become aware of the different aspects and socioscientific nature of these phenomena.

Environmental attitudes, environmental awareness, and feelings are rarely mentioned in the analyzed articles. They are, however, important to consider in subject aims. Personalized experiential learning makes learning meaningful and influences students' attitudes towards sustainable development (Murti et al., 2025). Attitudes refer to positive or negative feelings and a desire to learn subject content (Kahveci, 2023). According to Admiraal et al. (2022), students' learning outcomes deteriorate if they do not have a positive attitude during the learning process. Students' attitudes do not affect only their learning outcomes but also their willingness to act. Education can play an important role in promoting positive attitudes and knowledge acquisition (Christ et al., 2022). Teaching methods that support students' action-oriented knowledge acquisition and self-confidence are an essential part of developing higher-level functional abilities (Sinakou et al., 2019).

Environmental awareness is a deep understanding of the relationship between humans and the environment, as well as recognition of an individual's responsibility in maintaining ecosystem balance (Ballard et al., 2024; Gazoulis et al., 2022). It is an educational tool that helps people to understand the aesthetic, biological, and economic importance of preserving natural resources and minimizing the negative effects of man-made adaptations and alterations. Environmental awareness can be promoted by using inter-, trans-, and multidisciplinary approaches (Akinwumi, 2023). The development of students' critical awareness and relationship with nature (Oliveira et al., 2019) can be supported by creating a pluralistic learning environment, including ethical and political dimensions in discussions of sustainability issues, and encouraging students to express their values and feelings (Arntzen et al., 2025). By integrating locally relevant content into biology teaching through, for example, nature experiences, students' empathic relationship with nature and ecological literacy can be fostered, and their environmental responsibility and willingness to protect the environment can be strengthened (Purwasih et al., 2025).

The development of environmental attitudes, awareness, and emotions is a key aim from a global competence perspective (OECD, 2018). Global competence refers to the multidimensional ability to consider local, global, and intercultural issues, to understand and appreciate different perspectives and worldviews, and to act responsibly and respectfully with others to promote sustainability and well-being (OECD, 2018). Students' cognitive, social, and verbal relationships with ecosystems can be improved by developing their lexical ecological literacy (Jensen, 2025), i.e., an individual's conscious sense of place and awareness of their place in the world. Good lexical ecological literacy may support individuals to protect ecosystems both in their daily lives and as members of society. Bridging the gap between knowledge, attitudes, and behavior is essential for achieving sustainable development (Funa & Emberga Gabay, 2025).

The findings show that the development of factual and conceptual knowledge is emphasized more than other subject aims, as also stated in the study by Erduran and Dagher (2014). Educators should place more emphasis on scientific skills (Dogan & Kunt, 2017), environmental awareness and emotions (Ballard et al., 2024; Gazoulis et al., 2022), and attitudes (Kahveci, 2023), as well as on the ability to apply acquired knowledge in real-life situations, to increase students' understanding of living systems and the relationships between humans and nature.

6.3.2. Learning Objectives

Learning objectives provide the goals on which the curriculum is focused, facilitate the selection and organization of content, and make it possible to evaluate learning outcomes. In total, there are 608 mentions of learning objectives in this study. Cognitive learning is well represented in the analyzed studies, whereas psychomotor and affective learning are not.

The lowest-level subdomain, factual and conceptual learning, is often mentioned, and the subdomains tend to be remembered and understood. By contrast, the highest-level subdomain, create, is very rarely mentioned. The findings are in line with previous studies, which state that traditional biology education remains predominantly compartmentalized, focusing on isolated scientific concepts rather than broader integrative applications of knowledge (Yücel & Çalışkan, 2025).

In addition to factual and conceptual learning, psychomotor and affective learning are important to take into account in biology education. Novak's (2010) theory of constructivism suggests that meaningful learning should involve thinking, feeling, and acting, implying that good learning activities integrate the three domains of learning. Greater consideration of the psychomotor and affective domains in parallel to cognitive learning

could therefore improve learning experiences. Psychomotor learning encompasses hands-on learning and ranges from reflex movements and physical abilities to the performance of skilled movements. Affective learning refers to a learner's emotional state and includes motivational beliefs, values, and responses, as well as interaction with others (Findley & Woodruff, 1964). Affective learning with social skills is important to be emphasized for collaboration, negotiation, and communication to promote the SDGs, as well as self-reflection skills, values, attitudes, and motivation for enabling students to develop themselves.

Based on the findings, cognitive learning objectives are overrepresented compared to psychomotor and affective learning objectives. Furthermore, within cognitive learning objectives, there is a focus on the acquisition of factual and conceptual knowledge. Sipos et al. (2008) have stated that learning objectives should be holistic to develop students' ability to act on issues related to environmental, social, and economic sustainability in accordance with SDGs. Thus, biology education should foster students' sustainability mindset and cognitive flexibility as early as possible. This requires instilling the values of environmental stewardship, environmental awareness, and the importance of sustainable practices. All three learning objectives (cognitive, psychomotor, and affective learning) should be clearly defined so that students have an idea of what is expected of them in terms of sustainability competence.

The dataset analyzed in this study contained little research on the impact of subject aims and learning objectives in biology education. However, subject aims and learning objectives are not static and can be improved through teacher collaboration. More attention should be paid to their impact, especially concerning integrative teaching. Many concepts included in biology education have other meanings beyond their biological ones, which affects the design of subject aims and learning objectives. For example, sustainable development is a political concept that is used when trying to reconcile continuous economic growth with social and ecological challenges. Ecosystem service, on the other hand, is an economic concept that aims to appraise the values produced by nature so that they can be measured (Brondizio et al., 2019). Ecosocial education as an educational concept describes the educational ideals that SE should include (Salonen & Bardy, 2015).

By fostering students' will to acquire, apply, and evaluate scientific knowledge, environmental awareness, and affective dimensions in biology education, educators can support students to take responsibility for their decisions and actions and to be aware of their impact on sustainable development.

6.4. Knowledge Promoting Sustainable Development

In total, there are 316 mentions of the levels of *subject content knowledge* (SCK) in this study. The analyzed studies focus mainly on the lower levels of SCK (factual and conceptual knowledge), and the higher level of SCK (metacognitive knowledge) is mentioned only rarely. The findings are in line with the study of Yli-Panula et al. (2017b), where fundamental facts, such as species knowledge, the structure and function of living organisms and biological phenomena (e.g., photosynthesis), ecological issues (e.g., food chains or food webs), and understanding of the functions of nature as well as issues in human biology are seen as the most important issues.

The findings suggest that topics regarding the higher levels of SCK and the integration of the SDGs into biology teaching are not popular. This may be due to the fact that some teachers and student teachers have significant gaps in their interest and skills in teaching science, including biology (Backman et al., 2019; Efe & Umdu Topsakal, 2025; Palmberg et al., 2015; Yli-Panula et al., 2017a, 2017b). Furthermore, teaching sustainable development has not been sufficiently supported in teacher education (Albion et al., 2025). In other words, students understand sustainability concepts and have developed critical thinking

skills, but they are unable to practically create solutions due to a lack of guidance and channels. Teacher education has an important role to play in reversing this trend.

In biology, teaching and learning processes should focus on a holistic approach (Uitto & Saloranta, 2017). By integrating environmental issues and sustainability concepts from different subjects and fields in SCK, and by exploring the connections between scientific knowledge, social action, and ecological consequences, different aspects of the concept of sustainable development can be revealed. Thus, students may be able to form a holistic picture of ecosystems and sustainability and develop their interdisciplinary and multidisciplinary understanding of ecoliteracy (van de Wetering et al., 2022) to be ready for participation in action. Understanding local environmental conditions helps individuals to be more connected to and responsible for preserving nature around them. For example, recognizing the endangered plant and animal species in a particular area can encourage more focused conservation efforts. Therefore, local knowledge enriches insights and encourages concrete actions in maintaining regional biodiversity and ecosystem stability (Szczytko et al., 2018). In addition, combining SCK with real-life experiences can change students' attitudes, interests, and motivation towards studying biology (Almasri et al., 2021).

Effective *powerful knowledge* (systematic and specialized knowledge; Young, 2009) is mentioned in only three of the studies analyzed. Powerful knowledge needs to be emphasized more as biology education provides essential insights into ecosystems, biodiversity, and the processes that sustain life on Earth. Understanding biological systems is crucial for developing sustainable practices concerning environmental protection and improvement. Powerful knowledge that combines traditional ecological knowledge with modern scientific knowledge supports the creation of more comprehensive and culturally relevant sustainability strategies.

In biology teaching and learning, powerful knowledge is related (Uitto et al., 2024a) especially to the goals of Visions II and III (Roberts, 2007; Sjöström & Eilks, 2018). It allows the student to find reliable explanations for world phenomena, different ways of looking at the world, and to learn ways of acting that enable participation in social and ethical debate. For example, in Vision II, biology content areas such as ecology, biodiversity, and evolution are related to value considerations concerning natural values or human health and well-being (Aivelo & Uitto, 2021; Sá-Pinto et al., 2022; Tidemand & Nielsen, 2017). Many topics intersect with ecological, social, and economic sustainability (E. Jeronen et al., 2024; Uitto & Saloranta, 2017; Yli-Panula et al., 2022a). Ecology is related to, among other things, land use, the production and consumption of commodities, the loss of nature, and ways to protect biodiversity. Concerning Vision III, there are connections from biology topics to social sustainability themes, such as human rights and equality. Many topics also appeal to attitudes or emotions that should be taken into account in teaching. Such sensitive topics can include, for example, topics related to the well-being of people and nature (Ottander & Simon, 2021; Tidemand & Nielsen, 2017). Biology education has transformative power as students form new views based on their observations and insights regarding existing concepts and conceptual connections related to their living environment (Muller & Young, 2019).

Furthermore, based on the findings, pedagogical content knowledge (PCK) has also received very little attention. PCK should be emphasized more both in the planning and implementation of teaching and learning situations because it can support students in the acquisition of knowledge for sustainable action according to Vision III (Rockström & Sukhdev, 2016). When designing learning content, the higher levels of knowledge (metacognitive, evaluative, and reflective) that are important for sustainable development should be emphasized, taking into account students' needs so that the students can understand issues related to sustainable development in the intended way.

Biology curricula transform over time via a three-stage process (Gericke et al., 2025). First, teachers transform curricular knowledge into taught knowledge, thereby creating their own interpretation. Secondly, students learn a version of it and apply the knowledge they have learned in their lives outside of school. On the other hand, the students bring their experiences outside of school back into the classroom, which influences their acquisition of new knowledge at school. Finally, this influences curriculum design because measurements of learning outcomes are used as inputs by curriculum designers (Gericke et al., 2018).

To develop curricula and teaching and learning processes, educators should, rather than providing fragmented factual and conceptual information, use pedagogical content knowledge (PCK) to help students develop an integrative approach to biological phenomena by exploring their own and others' thinking, information, knowledge, and actions.

6.5. Teaching and Learning Methods Promoting Sustainable Development

In total, there are 446 mentions of teaching and learning methods in this study. Interactive teaching and learning methods are mentioned the most often, followed by student-centered methods. Teacher-centered methods are mentioned the least often. The most commonly chosen teaching methods to promote sustainable development in biology education at all educational levels are based on hands-on education. This finding supports the study of Yli-Panula et al. (2018), but the finding regarding teacher-centered working methods differs from the studies that indicate widespread reliance on textbooks and teacher-centered instruction (Hiltunen et al., 2021; Zhang et al., 2025).

In the analyzed studies, 49 different teaching and learning methods are mentioned. Based on the findings of this study, a wide range of both old and new teaching and learning methods are used in biology education. The findings suggest that there is a shift in biology education towards student-centered, collaborative, and experiential teaching and learning methods. Thus, the study strengthens the results of the previous studies about the importance of personal experiences and real-life issues in authentic environments for teaching and learning (Fu et al., 2025; Palmberg et al., 2019; Yli-Panula et al., 2018).

The following sections discuss the teaching and learning methods that are commonly used in biology education, starting with those mentioned most frequently, namely discussion, problem-solving, and cooperative and collaborative learning.

Discussion includes open collaborative exchanges of ideas between a teacher and students, or among students, with the aim of promoting student thinking, learning, problem-solving, understanding, or appreciation of the subject matter being taught. Students may discuss in pairs, small groups, or with the entire class and may be led by the teacher or students. Participants present perspectives, comment, and reflect on their own and others' ideas in an effort to build their knowledge, understanding, or interpretation of the topic being discussed, whether it be a written text or a problem, question, or issue. Considering improving students' critical thinking and communication skills, discussion is more effective and result-oriented as a teaching strategy than traditional lecturing (Saira & Hafeez, 2021). According to Yli-Panula et al. (2018), group discussions concerning the structure of a problem, the causes of the problem, and the potential responses to solve the problem from ecological, economical, and societal points of view are appropriate methods for studying ecological issues.

Matching the results of this study, Ölçer-Çevik and Kozaner (2025) have also stated that *problem-solving* is a popular teaching method. The findings differ from Fatmawati (2020), who argues that university-level teaching often lacks the teaching of problem-solving skills that lead to creative thinking. The reason for this difference in the findings can be that this study, unlike Fatmawati, concerns all educational levels from primary to higher education. Problem-solving can be applied at all educational levels. It aims to shift responsibility for

learning to the students and to actively engage students in learning with the instructor and other students (Cheng et al., 2019). In school education, problem-solving is often used in flipped classrooms, in which the majority of instructional delivery occurs outside the classroom, emphasizing "do-it-yourself" culture, hands-on creation, and design thinking (Bergmann & Sams, 2012). However, only four of the analyzed studies mentioned flipped classrooms. Instead, in the studies analyzed, as in the study of Abeysekera and Dawson (2015), problem-solving was used in active and social learning situations, where students were coached in advance so that they could fully benefit from classroom learning.

In *cooperative learning*, students work in small groups and share responsibility to achieve common goals. In this study, cooperative learning has been mentioned quite often, showing that it is a popular method. The results of the previous studies on cooperative learning are mixed. For example, studies by Slavin et al. (2022) show that cooperative learning has a significant positive effect on student learning levels. On the other hand, some studies have shown that its effects are varied or even negative. For example, a meta-analysis by Springer et al. (2022) showed that cooperative learning has no significant effect on students' learning levels in higher education. Despite these conflicting results, cooperative learning is a preferred teaching method for many teachers. It has been widely used, especially in comprehensive education, as a means to promote student engagement and collaboration.

Collaborative learning (commonly confusingly referred to as cooperative learning) is also commonly used in the analyzed studies. This method aims to promote student engagement, socialization, and learning (Yli-Panula et al., 2018). In collaborative learning, the level of commitment to achieving the shared goal is higher than in cooperative learning. When students collaborate, they can learn to listen to each other, to clarify misunderstandings, to provide help and support to others, and practice information-seeking. They can learn to discuss and draw conclusions together and build relationships that promote group cohesion, self-confidence, and trust.

In biology education, students can learn to construct knowledge and to create social meaning when examining, building, and applying, for example, biological, ecological, environmental, and conservation-related knowledge (Kontkanen et al., 2016). Collaboration inside schools and with local communities or organizations allows students to participate, for example, in species preservation or recycling programs, offering opportunities to apply theoretical knowledge to practical scenarios. Gaining first-hand experiences and beginning to see the impact of environmental action on the local ecosystem may deepen the students' understanding. First-hand experiences can promote their ecological awareness and environmental responsibility. This way, students may find solutions to reduce the impact of human activity on the environment for protecting and preserving their living environment. Participatory teaching methods can support transformative engagement and the development of active citizenship.

The subsequent most frequently mentioned teaching and learning methods are problem-based learning (PBL), inquiry-based learning (IBL), and project-based learning (PjBL).

The observation of the popularity of *PBL* (*problem-based learning*) supports the studies of Caeiro and Simão (2025) and Santos et al. (2025). PBL can promote critical and systems thinking (Chen et al., 2022), collaboration, and problem-solving (Cavadas & Linhares, 2023; Liu & Pásztor, 2022). It can also develop environmental and self-awareness skills (Wang, 2021). Based on student-centered learning, PBL offers an excellent approach to promoting cognitive flexibility (Honra & Monterola, 2025). Cognitive flexibility enables students to collectively critically examine the relationships between concepts, apply interdisciplinary approaches, and create innovative solutions to complex real-world problems (Wang, 2021). By combining information from multiple sources, students can find solutions, for example,

to ecological questions that require synthesizing knowledge from genetics, physiology, and environmental science. High cognitive flexibility can improve students' competence in solving modern scientific challenges (Honra & Monterola, 2025). Therefore, prioritizing the development of cognitive flexibility is essential in biology teaching.

The findings of this study support the study of Hubbard (2024), which shows that *IBL* (*inquiry-based learning*) is a popular teaching method in biology teaching. Integrating IBL as a teaching approach aims to develop the understanding of scientific ideas and the nature of science (NOS). IBL can facilitate the understanding and use of scientific practices in conjunction with learning subject matter ideas and principles, as well as support the development of thinking skills (Tal et al., 2019). IBL has several benefits for students, including improved scientific thinking and a sense of dedication to the work (Hubbard, 2024). Opportunities to participate in authentic scientific inquiry, research, and experimental science may allow students to see connections between the content being taught and "real-world" problems, to think critically, and to develop their field, laboratory, and experimental design skills (Hubbard, 2024).

IBL with ICT applications (virtual learning, simulations, and animations) can offer new learning experiences when the traditional school laboratory is combined with a virtual laboratory (Södervik, 2024). Augmented reality learning environments make possible, for example, the examination of microscopic things and processes, such as cell structures and cell division and molecular biology (Bennett & Saunders, 2019; Reen et al., 2022), as well as places and time dimensions (e.g., anoxic lake bottoms or melting glaciers) (Södervik, 2024). Thus, digital literacy—that is, the acquisition of information, as well as the understanding and investigation of biological concepts and phenomena using digital tools—has also emerged as a core skill in biology education.

The finding regarding the popularity of *PjBL* (*project-based learning*) supports the study of White et al. (2024). PjBL can promote active students' engagement and a deeper understanding of environmental challenges by incorporating hands-on creative activities into learning situations in real-world contexts (White et al., 2024). It can encourage students to identify environmental problems, design creative solutions, and implement them through collaboration, often with local communities or relevant stakeholders. Through interdisciplinary (White et al., 2024) and multidisciplinary strategies (Persano Adorno et al., 2025), the gap between scientific principles and real-world sustainability issues can be bridged for strengthening the environmental awareness of students. When students' understanding about the interactions between ecosystem components and human environmental impacts broadens, their sustainability skills may increase (Caeiro & Simão, 2025), and awareness of the importance of maintaining ecosystem sustainability and balance deepens (White et al., 2024). In addition, for example, by making their own materials and planting trees, students can learn practical skills, such as resource management and environmental restoration techniques.

In the analyzed studies, the methods of explanations, demonstrations, conversations, experiential learning, place-based and community-based education, and communication and interdisciplinary work are also mentioned quite often. Other commonly used teaching and learning methods are also discussed, although they are not mentioned as often as the methods described above.

Explanations, demonstrations, and conversations are suitable teaching strategies for introducing new concepts, processes, or skills to students. They are useful for providing clear and visual examples of how something works or how to perform a task. Explanation-oriented science teaching practice cognitively may activate students to use reasoning skills (i.e., to formulate scientifically oriented questions, to analyze and interpret data patterns, and to connect data patterns with theoretical entities to develop the causal chain of events)

and to develop evidence-based causal explanations of natural phenomena (Nawani et al., 2019). In demonstrations, the teacher performs the experiment in the class, explaining verbally what he/she does. The students can observe critically, help the teacher in performing the experiment, and try to draw inferences (Davar, 2025). Conversations play a major role in students' learning. They can be conducted either with the whole class, led by the teacher or a student, or in small groups with the students as the leaders. The flow and direction of the discussion are influenced by the development of the ideas presented and their accuracy (Cavagnetto et al., 2022). Thus, conversations can affect the students' learning outcomes, but the role of the teacher as an observer and as a supervisor is important. Explanations and conversations can help to clarify complex ideas in a simplified manner, while demonstrations can help learners to understand the practical application of theoretical concepts.

The findings of *experiential learning* are in line with the studies of Palmberg et al. (2019) and Yli-Panula et al. (2018). Experiential learning can encourage students to learn through real-life experiences by participating in activities that are designed to promote critical thinking and reflection (Fu et al., 2025). Interactions with nature and communities can enrich students' ecological knowledge, emotional attachment, and pro-environmental behavior (Zhao et al., 2024). According to Friman et al. (2024), experiential learning not only affects students' acquisition of knowledge but also produces a significant shift in their perceptions and attitudes toward sustainability as well as changes in behavior and action, indicating a broader societal impact. Some studies show that students' ecological awareness (Ardoin et al., 2018), scientific literacy (Hubbard, 2024), eco-literacy (Kazazoglu, 2025), and also their digital competencies can improve (Yeon et al., 2025). According to Savage et al. (2015), an experiential problem-based approach can develop the five key competencies identified by Wiek et al. (2011): systems thinking, anticipatory, strategic, interpersonal, and normative thinking. In addition, experiential learning may support personal competence, which is important in supporting the development of key competencies in sustainability (Savage et al., 2015).

Place-based education promotes the idea of spatial, embodied, and contextual learning about natural or human environments (Semken et al., 2017). Place-based learning is a natural part of learning biology. However, in this study, *fieldwork and field trips* are not mentioned very often. The finding differs from previous studies, where these have been found to be common teaching methods in biology teaching (Boyle et al., 2007; Lavie Alon & Tal, 2015). The low number of field trips and field work in this study may be due to the fact that, according to Lynch et al. (2025), although the program is designed to support and enhance teaching and learning, students often view the program as a social opportunity rather than an academic one. In addition, teachers and students may not believe that these work methods directly contribute to students' subject academic learning.

However, fieldwork and field trips can be seen as good teaching and learning methods. They appear to have positive effects on students' attitudes and behaviors toward sustainable development (Liefländer et al., 2013). They can also strengthen students' relationships with and connections to nature (Braun & Dierkes, 2017; Lankenau, 2018; Liefländer et al., 2013) and foster students' environmental awareness (Nazir & Pedretti, 2016).

Community-based learning is mentioned quite often. Its focus can be, for example, regional ecosystems and issues, having the potential to connect experiential learning and collaborative research with student interests and affinity for a particular area (Connors et al., 2021; Hiatt et al., 2021). Students work across institutions on joint scientific activities that not only may better reflect many of the faculty's research activities but also enhance students' understanding of their contributions to the broader scientific community.

Communication and interdisciplinary work are mentioned quite often in the analyzed studies. ElSayary (2024) has also stated that these teaching and learning methods are popular. According to her study, by combining knowledge, methods, and ways of thinking from different disciplines, explanations and sustainable solutions can be found for environmental, social, and economic problems (ElSayary, 2024). Hybrid classrooms are ideal for this purpose, but they were not mentioned in the analyzed studies. Hybrid classrooms are learning environments where communication and interdisciplinary work are integrated into teaching with the help of technology (Lei & Lei, 2019). Face-to-face teaching is partially replaced by self-directed online learning (Stromie & Baudier, 2017). Hybrid teaching includes various interactive learning strategies with different forms of interaction between students and between students and the teacher (Lei & Lei, 2019). It can include various teaching and learning methods, such as interactive app-based activities and small-group discussions (Kegley et al., 2016). Previous studies have shown that hybrid teaching effectively supports students in achieving learning goals (Tiahrt & Porter, 2016).

Online learning has several advantages, such as allowing students to work at their own pace and access learning materials at any time. However, hybrid education also presents challenges for both teachers and students. The challenges for teachers include time and workload (Kegley et al., 2016) as planning and implementing instruction can take more time than fully face-to-face instruction. The challenge for students is that they may think they have the skills needed for intensive digital learning when in reality they find hybrid learning more challenging than traditional face-to-face instruction (Comer et al., 2015). Careful overall planning of hybrid education based on learning objectives can help to overcome some of the challenges encountered (Stromie & Baudier, 2017).

Experimental learning is mentioned quite rarely in this study. The finding is in line with the study of Yli-Panula et al. (2018). Through *experimental learning*, students can conduct scientific experiments aiming to gain new knowledge or to confirm existing knowledge by researching the influence of different variables (Kolb, 1984). The students can be engaged in a learning process in which they reflect on their experiences to gain insights into problems and apply new knowledge to real-life situations. Experimental learning enhances learning and builds self-confidence and critical thinking. According to Sumleth and Walpuski (2012), experimental learning can also be carried out online. Jahnke (2012) states that online experimental learning is a special case of socio-technical learning, which is the process of research-based and experiential learning that combines individual and cooperative learning with opportunities to interact with other community members online or face-to-face. Online experimental learning can take place in remote laboratories via an online learning platform with internet access.

Educational games, role-playing, and visits are rarely mentioned and only used at the primary and secondary levels. The findings support the study of Yli-Panula et al. (2018). However, they may have multiple benefits for all educational levels. For example, educational games can be used to activate students to participate and interact (C. S. Green & Bavelier, 2012). Role-playing in science teaching and learning can encourage students to participate in the lesson, express themselves in a scientific context, and develop their understanding of biological concepts (Yli-Panula et al., 2018). Through visits to, for example, recycling events or waste sorting plants, students can be offered learning experiences related to ecological sustainability. These kinds of teaching and learning methods may support students' learning in cognitive, affective, and psychomotor learning dimensions (cf. Sipos et al., 2008) for promoting sustainable development.

Approaches with a creative and motivating component, such as art education, ecological design, and indigenous education, may offer good opportunities for strengthening nature connection through sustainability-oriented learning. Also, other innovative pedagog-

ical approaches and methods, such as the whole-school approach and fore- and backcasting methods, may be useful for supporting students' understanding of complex sustainability challenges and solutions. Especially, new technologies (AI and the various applications of extended reality XR: augmented reality, AR; virtual reality, VR; and mixed reality, MR) may play an increasingly important role in the development of sustainable societies in the future. They can enable deeper exploration of difficult concepts and topics, offering a diverse and interactive approach to biology teaching and learning (Sangur et al., 2025; Södervik et al., 2021). This in turn enables the discovery of new behaviors and actions that promote sustainable development. Digital literacy can thus be seen as an important skill in biology teaching and learning. However, further research is needed, for example, on whether virtual learning experiences have as strong an impact on learning outcomes as real hands-on learning experiences as young generations are generally familiar with virtual experiences, including fictional ones.

Traditional teaching methods, while effective in conveying content, often fail to fully engage students, foster curiosity, or encourage them to think critically and solve real-world problems. New methods often have a strong student-centered approach, which is in line with the constructivist paradigm of Novak (2010). They include varying degrees of student-centered practices, where students take more responsibility for acquiring knowledge, competencies, and skills than in traditional teaching methods. In biology teaching, innovation is crucial to making learning more interactive, meaningful, and engaging. Innovative teaching methods—such as inquiry-based learning, project-based learning, and technology integration—provide opportunities for students to actively explore biology, develop problem-solving skills, and connect what they are learning to their own lives.

Educators can help students to develop an integrative approach to biological phenomena, and discover new perspectives and practices promoting sustainable development, by using diverse teaching and learning methods that activate students and are contextualized to real-life situations. By using modern approaches, they can make biology lessons more dynamic and stimulating, encouraging students to see the subject as a living evolving discipline rather than a collection of static facts.

6.6. Assessment Methods Fostering Sustainability Competencies

In biology education, several methods and strategies can be used to evaluate and assess students' sustainability learning. However, based on the findings, the assessment of students' learning on sustainability competencies received relatively little attention, with only 49 mentions in total. The result supports the study of Annelin and Boström (2023), according to which students' sustainability skills are inadequately assessed.

Based on the findings, summative and formative methods are used more often than diagnostic methods. From the measurement types, the teacher's ongoing monitoring of students' learning progress, the teacher's continuous feedback, tests, and exams are mentioned more often than other ones. Assessment strategies should be developed based on the learning objectives in relation to students' needs. Regular evaluations of teaching and learning help to detect how effective the employed pedagogical and didactic approaches focused on sustainable development have been. They provide students with information about their performance in relation to curriculum goals. Self-testing has great potential for substantially improving learning efficiency.

Continuous assessment requires additional effort and resources, but it can improve students' learning outcomes. The effectiveness of formative assessment has not been well studied yet (Morris et al., 2021), but it may be a useful method for teaching and learning about sustainable development. Summative assessment can be used to support students' thinking and action in line with SDGs. Summative assessment is in line with

constructivist learning theory (Vygotsky, 1978) by promoting collaborative knowledge construction through group-based inquiry. It also emphasizes experiential learning (Kolb, 1984), active engagement in problem-solving, reflection, and the application of concepts in real-world contexts. When assessment is based on the taxonomy of Bloom et al. (1956), students' cognitive skills, such as analysis, synthesis, and evaluation of environmental challenges, can also be examined at the higher levels of thinking skills.

Sustainable development and sustainable education are broad and multidimensional topics, and assessing their learning is challenging. In addition, for assessing knowledge and skills according to the criteria defined in the curricula, the key assessment objectives include thinking, argumentation, and research skills, including the ability to critically evaluate information (Uitto et al., 2024b). By employing active participation and interactivity, collaborative learning environments, and comprehensive evaluation tools, teacher educators and school teachers can effectively measure and enhance the impact of sustainable education in biology, ensuring thatstudents' knowledge, skills, and attitudes to address environmental challenges can be developed.

Assessment supports both the work of teachers and the learning of students. Using various assessment methods, educators can support not only the development of teaching and learning processes but also the development of curricula (Lyon, 2013).

6.7. Biology Education in Relation to Transformative Teaching and Learning

In biology, it is crucial to engage students in sustainability development practices through developing the desire and will to act in a sustainable way (Uitto et al., 2015). For this, transformative education is needed (Odell et al., 2019). It means that students' learning moves from adding knowledge to critical reflection on knowledge, and students should reflect on and work on, for example, their own worldview and preconceptions (Aboytes & Barth, 2020). Transformative education includes agency, participation, and a solution-oriented approach. It supports the understanding and application of scientific knowledge and methods, as well as commitment to actions that strengthen sustainable development (Sjöström & Eilks, 2018). Transformative learning (renewing learning) is thus a process of becoming aware of previously unquestioned assumptions, or frames of reference, and thus transforming the students to become more open and reflective.

Transformative teaching calls for a transformative action-oriented education that supports self-directed learning, participation and collaboration, problem orientation, interdisciplinarity, and transdisciplinarity (UNESCO, 2017a).

Interdisciplinarity combines knowledge, methods, and ways of thinking from two or more disciplines to achieve cognitive progress, such as explaining a phenomenon, solving a problem, or creating a product (ElSayary, 2024). Interdisciplinary teaching is a method or a set of methods that are used to teach across curricular disciplines, or the bringing together of separate disciplines around common themes, issues, or problems (Ellis & Stuen, 1998). Interdisciplinary learning should create knowledge that is more holistic than knowledge built in discipline-specific studies.

Transdisciplinarity is an adaptive and problem-oriented approach that integrates knowledge and methods from different scientific disciplines and collaborates with stakeholders. Transdisciplinary teaching involves a paradigm shift seeking a balance between knowledge and transdisciplinary skills but arguing for an emphasis on skills, encompassing social relatedness, research skills, and the enhancement of thinking, communication, and self-management skills (Holbrook et al., 2020). Transdisciplinary learning is an educational approach that transcends the boundaries of traditional disciplines (e.g., arts, natural sciences, and social sciences). It enables students to explore concepts, issues, or problems by

integrating perspectives from multiple disciplines, connecting new knowledge to real-life experiences, and fostering a deeper understanding of the world (Fam et al., 2018).

Transformative biology education for promoting sustainable development can be summarized as presented in Figure 12.

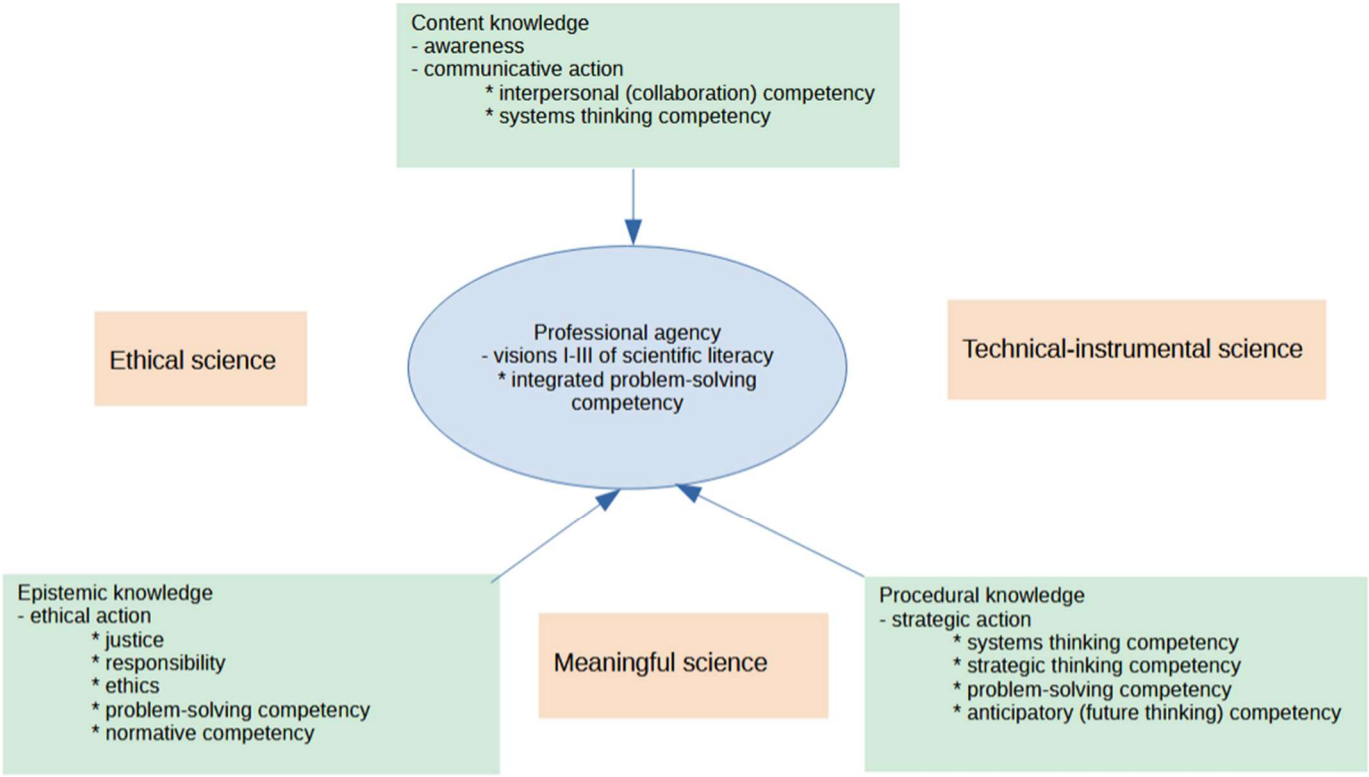


Figure 12. Transformative biology education for promoting sustainable development (cf. E. Jeronen et al., 2024).

According to E. Jeronen et al. (2024), knowledge of environmental and scientific issues is the starting point for transformative science education when promoting sustainable development. This consists of awareness towards the environment and research-based knowledge. Communicative action includes interpersonal skills, systems thinking skills, and problem-oriented competence. Developing these skills can improve the ability to convey messages, build positive relationships, and communicate in ways that respond to challenges, find solutions, and encourage collaboration in problem-solving. Procedural interdisciplinary knowledge is needed for reasoning and decision-making concerning sustainability-related issues. Epistemic knowledge is also important. It requires the ability to distinguish between the essence of truth and the process of justification, as well as the management and research of factual information (Knight et al., 2014).

Transformative science education that promotes sustainability includes Visions I–III (Roberts, 2007; Sjöström & Eilks, 2018). Teaching based on these visions may help students to develop the knowledge, skills, and attitudes necessary to contribute to a sustainable future. However, thinking and envisioning the future involves making decisions based on uncertain information. Also, limited information processing and thinking skills can hinder learning and the belief in one's own potential for influence. Building realistic hope is an important goal when developing students' readiness to face uncertainty, learn future thinking skills, and become aware of one's own potential for influence.

6.8. Limitations

The limitations of the study are as follows. First, the findings are only based on the studies listed in the bibliographical database Scopus. Other databases could also be used to improve and compare the results. Also, due to the fact that Scopus includes mostly articles that are written in English and the search was conducted only in English, there is language bias. Also, the uneven distribution of research volumes between the USA and other countries may bias the interpretation of the results.

The bibliometric analysis step was based on titles and abstracts. This could be extended to include keywords. However, because all studies do not necessarily provide keywords in their metadata and datasets can be large, an automatic method to extract keywords from free-form text (abstracts or full text) is needed. Possible approaches include classical frequency-analysis-based methods and AI-based methods, such as performing free-form text analysis of each study with a large language model (LLM).

The literature was automatically clustered semantically, leaving a few data points as outliers. Other methods may result in different groupings of the studies reviewed.

Due to the automatic analysis method used, the outliers likely arose from spurious linguistic similarities of the title and abstract between the outlier data point and the data points in the cluster into which the algorithm placed the outlier. One possible source of this spurious similarity includes surface-level linguistic similarities that are not topic similarities. Another is that the semantic embedding model is not perfect, which may cause artifacts. Finally, while the normalization of the semantic vectors to unit length is convenient to make them comparable via cosine distance, it has the effect of collapsing all the vectors pointing in the same direction into a single point on the hypersphere surface. This may be important if the distance from the origin happens to encode information.

A limitation of the scope of this study is that the analysis is based only on published research. To obtain a fully up-to-date view, other research methods could be used, such as interviews of teachers and students, as well as monitoring of teaching and learning processes.

6.9. Future Research

Future research can further advance the theory of innovative biology curricula based on sustainable development goals, especially by integrating new disciplines such as synthetic biology, synthetic ecology, and bioinformatics (Hu et al., 2025). The inclusion of multidisciplinary theories can develop a more comprehensive and systematic framework for curriculum innovation, improving both the theoretical depth and breadth of biology education (Tilbury, 2011).

Future research should focus on different SE pedagogical and didactic approaches in biology education in teacher education and at schools. The findings show that the use of teacher-centered methods is clearly lower than the use of interactive and student-centered methods. This suggests that the importance of teacher-centered methods has decreased. New methods based on the constructivist paradigm may better support sustainable learning as they place more responsibility on students for acquiring knowledge and skills than previous methods. However, further research is needed to confirm this.

Further empirical research is also needed to explore how, through SE in biology education, students' sustainability thinking and competencies can be effectively developed and assessed in classroom settings. The integration of digital technologies, such as virtual learning environments and AI applications, into biology education fostering SE needs to be explored.

The findings emphasize a need for comparative studies of pedagogical and didactic approaches and their evaluations in relation to the expected learning outcomes. Longitu-

dinal studies are crucial for assessing the long-term impact of SE in biology education on students' attitudes and behaviors toward sustainability.

This research offers new ideas for reforming biology teaching. As all teaching situations are context- and subject-specific, it is not possible to compile a general list of the most or least effective teaching principles and ideas. However, from a practical perspective, the analyses offer ideas on how these findings can be used to promote a transformative approach and sustainability considerations in biology teaching and curriculum development. Although the analyses of recent research on biology teaching objectives, content knowledge, teaching and learning methods, and assessment methods provide many details, understanding teaching and learning requires a holistic view of educational processes with all their implications. Future research should aim to explore these theoretical debates in more detail and utilize new theoretical debates and cross-disciplinary collaborations to promote sustainability in a future-oriented way to improve students' sustainability skills in a holistic manner.

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Appendix A. Clustered Studies (* Not Reviewed in the Content Analysis)

Abramovich, A., & Loria, Y. (2015). The long-term impact of an education for sustainability course on Israeli science and technology teachers' pro-environment awareness, commitment and behaviour. *Australian Journal of Environmental Education*, *1*(2), 264–279. https://doi.org/10.1017/aee.2015.31.

Adeika, B. I., Ariyibi, A., Abiodun, P. O., & Oludare Adegbola Owolabi, P. E. (2024, June 23–26). *Breaking barriers: Promoting motivation, engagement, and learning success among biology undergraduates from minority backgrounds*. 2024 Annual Conference and Exposition, Oregon Convention Center, Portland, OR, USA. https://doi.org/10.18260/1-2--48406.

Akpınarlı, S. S., & Turan, S. L. (2023). An examination of reproduction and development in secondary school biology curricula: Türkiye and Germany. In M. Koc, O. T. Ozturk, & M. L. Ciddi (Eds.), *Proceedings of ICRES 2023—International conference on research in education and science, Cappadocia, Turkiye* (pp. 1854–1865). ISTES Organization. Available online: https://eric.ed.gov/?id=ED654312 (accessed on 22 January 2026).

Al-Muqbil, N. S. M. (2024). The impact of an artificial intelligence application-based training program on developing sustainable thinking among high school biology teachers. *Educational Sciences: Theory and Practice*, *24*(1), 201–215. Available online: https://psau.sa.elsevierpure.com/en/publications/the-impact-of-an-artificial-intelligence-application-based-traini/ (accessed on 22 January 2026).

* Alordiah, C. O. (2023). Mind the gap: Exploring effectice strategies for conducting gap analysis in educational studies. *Journal of Contemporary Issues in Education*, *7*(1), 239–252. Available online: https://www.researchgate.net/publication/374420184_MIND_THE_GAP_EXPLORING_EFFECTIVE_STRATEGIES_FOR_CONDUCTING_GAP_ANALYSIS_IN_EDUCATIONAL_STUDIES (accessed on 22 January 2026).

Amprazis, A., & Papadopoulou, P. (2024). Key competencies in education for sustainable development: A valuable framework for enhancing plant awareness. *Plants People Planet*, *7*(4), 1195–1211. https://doi.org/10.1002/ppp3.10625.

* Araripe, E., & Zuin Zeidler, V. G. (2024). Advancing sustainable chemistry education: Insights from real-world case studies. *Current Research in Green and Sustainable Chemistry*, *9*, 100436. https://doi.org/10.1016/j.crgsc.2024.100436.
Ariely, M., & Yarden, A. (2018). Using authentic texts to promote disciplinary literacy in biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 205–216). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-17/using-authentic-texts-promote-disciplinary-literacy-biology-moriah-ariely-anat-yarden?context=ubx&refId=91c051c8-1a53-4ec3-aeb2-e3d5e864c132 (accessed on 22 January 2026).
* Arita, H. T. (2017). Multisite and multispecies measures of overlap, co-occurrence, and co-diversity. *Ecography*, *40*(6), 709–718. https://doi.org/10.1111/ecog.01942.
Assaraf, A. B. Z., & Snapir, Z. (2018). Human biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 62–73). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-6/human-biology-orit-ben-zvi-assaraf-zohar-snapir?context=ubx&refId=f480597a-8cf1-4f82-9ed9-d86eee429278 (accessed on 22 January 2026).
Bacon, C. M., Mulvaney, D., Ball, T. B., DuPuis, E. M., Gliessman, S. R., Lipschutz, R. D., & Shakouri, A. (2011). The creation of an integrated sustainability curriculum and student praxis projects. *International Journal of Sustainability in Higher Education*, *12*(2), 193–208. https://doi.org/10.1108/14676371111118237.
Baena-Morales, S., Vásquez-Echeverría, A., Gavilán-Martín, D., & González-Villora, S. (2024). Psychological approaches to sustainability: Implementing intervention model for sustainable development in physical education. *Sustainable Development*, *32*, 5692–5704. https://doi.org/10.1002/sd.2986.
Bara, E., Bara, G., & Pupe, S. (2024). The role of biology curriculum in promoting student health, environmental awareness, and academic success: Teacher responsibilities. *Edelweiss Applied Science and Technology*, *8*(2), 1–14. https://doi.org/10.55214/25768484.v8i2.1081.
Barraza, L., & Castaño, C. (2012). Can science education help to build a sustainable society? *Profesorado, Revista de Currículum y Formatión del Professorado*, *16*(2), 45–58. https://www.redalyc.org/articulo.oa?id=56724395004 (accessed on 22 January 2026).
Bass, C. (2012). Learning theories & their application to science instruction for adults. *American Biology Teacher*, *74*(6), 387–390. https://doi.org/10.1525/abt.2012.74.6.6.
Bezeljak, P., Scheuch, M., & Torkar, G. (2020). Understanding of sustainability and education for sustainable development among pre-service biology teachers. *Sustainability*, *12*, 6892. https://doi.org/10.3390/su12176892.
Biletska, H., Mironova, N., Yefremova, O., Barna, L., & Bloshchynskyi, I. (2021). The future biology teachers training for the implementation of sustainable development ideas in ecological education. *International Journal of Innovative Research and Scientific Studies*, *4*(4), 229–237. https://doi.org/10.53894/ijirss.v4i4.200.
Brandt, J.-O., Barth, M., Merritt, E., & Hal, A. (2021). A matter of connection: The 4 Cs of learning in pre-service teacher education for sustainability. *Journal of Cleaner Production*, *279*, 123749. https://doi.org/10.1016/j.jclepro.2020.123749.
Brody, S. D., & Ryu, H. (2006). Measuring the educational impacts of a graduate course on sustainable development. *Environmental Education Research*, *12*(2), 179–199. https://doi.org/10.1080/13504620600688955.
Byrne, J., & Grace, M. (2018). Health and disease. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 74–86). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-7/health-disease-jenny-byrne-marcus-grace?context=ubx&refId=82cd02bb-c652-4c86-9acd-86089f4a6b11 (accessed on 22 January 2026).

* Cabral, S., & Kaivola T. (2005). Imagine the world. *Teaching Geography*, *30*(2), 86–90. Available online: https://www.jstor.org/stable/44633441 (accessed on 22 January 2026).
* Capello, M. A., Shaughnessy, A., & Caslin, E. (2021). The geophysical sustainability atlas: Mapping geophysics to the UN sustainable development goals. *The Leading Edge*, *40*(1), 10–24. https://doi.org/10.1190/tle40010010.1.
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.
Carson, K., Dawson, V., & Venville, G. (2018). Microbiology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 178–192). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-15/microbiology-katherine-carson-vaille-dawson-grady-venville?context=ubx&refId=240ce8f4-bae3-4640-9a92-3bec7a0df019 (accessed on 22 January 2026).
Cheng, L.-T., Smith, T. J., Hong, Z.-R., & Lin, H.-s. (2021). Gender and STEM background as predictors of college students' competencies in forming research questions and designing experiments in inquiry activities. *International Journal of Science Education*, *43*(17), 2866–2883. https://doi.org/10.1080/09500693.2021.1994167.
Church, W., & Skelton, L. (2013). Infusing sustainability across the curriculum. In R. McKeown, & V. Nolet (Eds.), *Schooling for sustainable development in Canada and the United States* (pp. 183–195). Schooling for Sustainable Development, 4. Springer. https://doi.org/10.1007/978-94-007-4273-4_13.
Chuvieco, E., Carrillo-Hermosilla, J., López-Mújica, M., Campo-López, E., Lazo-Vitoria, X. A., Macias-Guarasa, J., Petre-Bujan, A. L., Perdigón-Melón, J. A., Guardiola-Soler, J., & Salado-García, M. J. (2022). Inventory and analysis of environmental sustainability education in the degrees of the University of Alcalá (Spain). *Sustainability*, *14*, 8310. https://doi.org/10.3390/su14148310.
* Conde-Caballero, D., Castillo, C. A., Ballesteros-Yáñez, I., & Mariano-Juárez, L. (2019). Blogging as a tool for the acquisition and dissemination of knowledge in health sciences: A preliminary evaluation. *International Journal of Educational Technology in Higher Education*, *16*(1), 30. https://doi.org/10.1186/s41239-019-0161-2.
Copeland Solas, E., & Wilson, K. (2015). Lessons learned and strategies used while teaching core-curriculum science courses to English language learners at a middle eastern university. *Journal of Turkish Science Education*, *12*(2), 81–94. Available online: https://zu.elsevierpure.com/en/publications/lessons-learned-and-strategies-used-while-teaching-core-curriculu-2/ (accessed on 22 January 2026).
Courter, J. R. (2012). Graduate students in conservation biology: Bridging the research-implementation gap. *Journal for Nature Conservation*, *20*(1), 62–64. https://doi.org/10.1016/j.jnc.2011.10.001.
Danilov, S., & Danilova, O. (2013). An integrated approach to the study of biology. In L. V. Shavinina (Ed.), *The Routledge international handbook of Iinovation education.* Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9780203387146-43/integrated-approach-study-biology-sergei-danilov-olga-danilova?context=ubx&refId=c07abaef-b670-40a4-af84-1a8f57e778e6 (accessed on 2022 January 2026).
da Silva, N. C., & de Araújo, F. M. F. (2022). The SDGs and the perspective of education for sustainability in the educational program of undergraduate biology courses in the Amazon region of Pará. *Sustainability in Debate—Brasília*, *13*(2), 32–48. https://doi.org/10.18472/SustDeb.v13n2.2022.42251.
da Silva, N. C., & de Araújo, F. M. F. (2024). Education for the sustainability of teaching practice in degree courses on biology in the state of Pará within the Aamazon area. *Educação*

e Pesquisa (Education and Recearch), *50*, e270602. https://doi.org/10.1590/S1678-4634202450270602por.

Day, D., Guo, C., Ferrari, N., Edgecumbe, H., & Broadbridge, C. (2013). Optimizing K-14 instruction to infuse 21st century skills. *MRS Online Proceedings Library*, *1583*, 306. https://doi.org/10.1557/opl.2013.776.

Desa, S., Abdullah, M. S., Ab Mutalib, N. H., & Mansor, R. (2021). The readiness of integrating sustainable development into biology teacher education program. *Cakrawala Pendidikan*, *4*(2), 305–315. https://doi.org/10.21831/cp.v40i2.37116.

Douglas, F., Beasy, K., Sollis, K., & Flies, E. J. (2024). Online, experiential sustainability education can improve students' self-reported environmental attitudes, behaviours and wellbeing. *Sustainability*, *16*, 2258. https://doi.org/10.3390/su16062258.

Dönmez, I. (2024). Sustainability in educational research: Mapping the field with a bibliometric analysis. *Sustainability*, *16*, 5541. https://doi.org/10.3390/su16135541.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education*, *84*(3), 287–312. https://doi.org/10.1002/(SICI)1098-237X(200005)84:3<287::AID-SCE1>3.0.CO;2-A.

Duncan, R. G., & Boerwinkel, D. J. (2018). Molecular biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 35–47). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-4/molecular-biology-ravit-golan-duncan-dirk-jan-boerwinkel?context=ubx&refId=df9d8ec3-1c73-4f82-a413-b4c6a0cab7f6 (accessed on 22 January 2026).

* Du Toit, E. (2024). Thirty years of sustainability reporting: Insights, gaps and an agenda for future research through a systematic literature review. *Sustainability*, *16*, 10750. https://doi.org/10.3390/su162310750.

Edwards, B. I., Aris, B., Shukor, N. A., & Mohammed, H. (2015). Using response system through voting in peer instruction for learning sustainability. *Jurnal Teknologi*, *77*(13), 147–157. https://doi.org/10.11113/jt.v77.6371.

* EI Kharki, K., Berrada, K., & Burgos, D. (2021). Design and implementation of a virtual laboratory for physics subjects in Moroccan universities. *Sustainability*, *13*, 3711. https://doi.org/10.3390/su13073711.

* Ergazaki, M. (2018). Biology and young children. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 9–10). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-3/biology-young-children-marida-ergazaki?context=ubx&refId=5f508608-8ac5-4f42-9715-ac066e89c95d (accessed on 22 January 2026).

Evans, E. M., & Rosengren, K. S. (2018). Cognitive biases or cognitive bridges? Intuitive Reasoning in Biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 9–34). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-2/cognitive-biases-cognitive-bridges-evelyn-margaret-evans-karl-rosengren?context=ubx&refId=ef7efae5-a38a-4680-b9e1-d5ebac438d45 (accessed on 22 January 2026).

Fadzil, H. M., & Saat, R. M. (2020). Exploring secondary school biology teachers' competency in practical work. *Jurnal Pendidikan IPA Indonesia*, *9*(1), 116–123. https://doi.org/10.15294/jpii.v9i1.21477.

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. *E3S Web Conference*, *568*, 04025. https://doi.org/10.1051/e3sconf/202456804025.

* Fayomi, O. S. I., Okokpujie, I. P., & Fayomi, G. U. (2019). An innovation concept towards bridging the gaps between teaching and research. *Procedia Manufacturing*, *35*, 775–781. https://doi.org/10.1016/j.promfg.2019.06.022.

Ferrer-Estévez, M., & Chalmeta, R. (2021). Integrating sustainable development goals in educational institutions. *The International Journal of Management Education*, *19*, 100494. https://doi.org/10.1016/j.ijme.2021.100494.

Fisher, P. B., & McAdams, E. (2015). Gaps in sustainability education: The impact of higher education coursework on perceptions of sustainability. *International Journal of Sustainability in Higher Education*, *16*(4), 407–423. https://doi.org/10.1108/IJSHE-08-2013-0106.

* Fox, P., Hundley, S., Cowan, D. J., Tabas, J., & Goodman, D. (2009, August 2–6). *Teaching sustainability: Course, program and degree considerations*. PICMET 2009 Proceedings (pp. 2240–2245), Portland, OR, USA. https://doi.org/10.1109/PICMET.2009.5261847.

Förtsch, C., Werner, S., von Kotzebue, L., & Neuhaus, B. J. (2018). Effects of high-complexity and high-cognitive-level instructional tasks in biology lessons on students' factual and conceptual knowledge. *Research in Science & Technological Education*, *36*(3), 353–374. https://doi.org/10.1080/02635143.2017.1394286.

Fuentes, A.-L., & Entezari, M. (2020). Water in your neighbourhood: A model for implementing a semester-long course-based undergraduate research project in introductory biology. *Education Inquiry*, *11*(3), 211–275. https://doi.org/10.1080/20004508.2020.1716542.

Gaard, G. C., Blades, J., & Wright, M. (2017). Assessing sustainability curriculum: From transmissive to transformative approaches. *International Journal of Sustainability in Higher Education*, *18*(7), 1263–1278. https://doi.org/10.1108/IJSHE-11-2015-0186.

Galante, D., Tassistro, M., & Torreggiani, A. (2024, March 14–15). *The Crystal Lake's Mystery: Interactive eco-crime game for learning about environmental sustainability*. New Perspectives in Science Education—International Conference, Florence, Italy. Available online: https://conference.pixel-online.net/files/npse/ed0013/FP/8788-ENV6438-FP-NPSE13.pdf (accessed on 22 January 2026).

Garibay, J. C., Vincent, S., & Ong, P. (2020). Diversity content in STEM? How faculty values translate into curricular inclusion unevenly for different subjects in environmental and sustainability programs. *Journal of Women and Minorities in Science and Engineering*, *26*(1), 61–90. https://doi.org/10.1615/JWomenMinorScienEng.2020029900.

* Gatti, L., Ulrich, M., & Seele, P. (2019). Education for sustainable development through business simulation games: An exploratory study of sustainability gamification and its effects on students' learning outcomes. *Journal of Cleaner Production*, *207*, 667–678. https://doi.org/10.1016/j.jclepro.2018.09.130.

Gericke, N., & El-Hani, C. N. (2018). Genetics. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 111–124). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-10/genetics-niklas-gericke-charbel-el-hani?context=ubx&refId=05b5156c-bfb9-455d-8834-d44edb9969e7 (accessed on 22 January 2026).

Ghazian, N., & Lortie, C. J. (2024). Ten simple rules for incorporating the UN Sustainable Development Goals (SDGs) into environmental and natural science courses. *Sustainability*, *16*, 9594. https://doi.org/10.3390/su16219594.

Goi, C. L. (Ed.). (2024). *Teaching and learning for a sustainable future: Innovative strategies and best practices.* IGI Global. https://doi.org/10.4018/978-1-6684-9859-0.

* Gulikers, J., & Oonk, C. (2019). Towards a rubric for stimulating and evaluating sustainable learning. *Sustainability*, *11*, 969. https://doi.org/10.3390/su11040969.

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*, *27*, 25381–25402. https://doi.org/10.1007/s10668-024-04733-z.

Hamman, M. (2018). Biotechnology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 192–203). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-16/biotechnology-marcus-hammann?context=ubx&refId=dceddb33-ca12-43b6-8048-c079f765921c (accessed on 22 January 2026).

Hardyanto, Y. S. P., Ibrohim, I., Sueb, S., Memiasih, N., & Alvionita, D. (2024). The effect of using problem-oriented project-based learning in biology electronic module to empower problem-solving of high school students. *AIP Conference Proceedings*, *3106*(1), 030039. https://doi.org/10.1063/5.0215079.

Harland, T., & Wald, N. (2018). Curriculum, teaching and powerful knowledge. *Higher Education*, *76*, 615–628. https://doi.org/10.1007/s10734-017-0228-8.

Harms, U., & Bertsch, U. (2018). Energy, photosynthesis and respiration. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 139–153). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-12/energy-photosynthesis-respiration-ute-harms-uwe-bertsch?context=ubx&refId=6baa6121-bdc7-4915-8da1-8608d012e37e (accessed on 22 January 2026).

Hartadiyati, E., Wiyanto, Rusilowati, A., & Prasetyo, A. P. B. (2020). Pedagogical content knowledge (PCK) of prospective biology teacher on respiratory system material to education for sustainable development. *Journal of Physics: Conference Serie*, *521*, 042034. https://doi.org/10.1088/1742-6596/1521/4/042034.

Hartadiyati, E., Wiyanto, Rusilowati, A., & Priyono, A. (2019). Representation of sustainability concept in prospective biology teacher learning. *Journal of Physics: Conference Series*, *1321*, 032053. https://doi.org/10.1088/1742-6596/1321/3/032053.

* Hawa, N. N., Zakaria, S. Z. S., Razman, M. R., & Majid, N. A. (2021). Geography education for promoting sustainability in Indonesia. *Sustainability*, *13*(8), 4340. https://doi.org/10.3390/su13084340.

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*, 12028. https://doi.org/10.3390/su132112028.

Howell, R. A. (2021). Engaging students in education for sustainable development: The benefits of active learning, reflective practices and flipped classroom pedagogies. *Journal of Cleaner Production*, *325*, 129318. https://doi.org/10.1016/j.jclepro.2021.129318.

Jackson, W. M., Binding, M. K., Grindstaff, K., Hariani, M., & Koo, B. W. (2023). Addressing sustainability in the high school biology classroom through socioscientific issues. *Sustainability*, *15*, 5766. https://doi.org/10.3390/su15075766.

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), 1. https://doi.org/10.3390/educsci7010001.

Jiménez-Aleixandre, M. P., & Evagorou, M. (2018). Argumentation in biology education. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 249–261, ISBN 978-1-315-11015-8). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-20/argumentation-biology-education-mar%C3%ADa-pilar-jim%C3%A9nez-aleixandre-maria-evagorou?context=ubx&refId=65b354be-6d0e-46f5-85c9-76386ec87001 (accessed on 22 January 2026).

Kampourakis, K., & Niebert, K. (2018). Explanation in biology education. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 236–248, ISBN 978-1-315-11015-8). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-19/explanation-biology-education-kostas

-kampourakis-kai-niebert?context=ubx&refId=09bfc95a-854f-4022-a4b4-00b755152b64 (accessed on 22 January 2026).
Kampourakis, K., & Stasinakis, P. K. (2018). Development. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research*, *issues*, *and trends* (pp. 98–110). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-9/development-kostas-kampourakis-panagiotis-stasinakis?context=ubx&refId=a1d9192e-186f-4283-8be1-381f97905036 (accessed on 22 January 2026).
Karimov, N., Turobov, S., Janzakov, A., Navotova, D., Ongarov, M., Inogamova, D., Pardaeva, K., & Nematov, O. (2024). Exploring food processing in natural science education: Practical applications and pedagogical techniques. *Natural and Engineering Sciences*, *9*(2), 359–375. https://doi.org/10.28978/nesciences.1574453.
Kennedy, B., Buikema, A., & Nagel, J. K. S. (2015, March 7). *Integrating biology*, *design*, *and engineering for sustainable innovation*. ISEC 2015—5th IEEE Integrated STEM Education Conference (pp. 88–93), Princeton, NJ, USA. https://doi.org/10.1109/ISECon.2015.7119952.
Kessler, C. (2018). Re-connecting design, education, and sustainability: The essential role of research in higher education curriculum development. *The International Journal of Sustainability in Economic*, *Social and Cultural Context*, *14*(1), 15–24. http://doi.org/10.18848/2325-1115/CGP/v14i01/15-24.
* Khanipoor, F., Bazrafkan, L., Aramesh, S., Shojaei, M., & Ghasemi, A. (2024). A study of medical students' experiences at Shiraz University of medical sciences from the implementation of integration in medical education: A qualitative study. *BMC Medical Education*, *24*(1), 1042. https://doi.org/10.1186/s12909-024-05983-1.
Kirkpatrick, C., Schuchardt, A., Baltz, D., & Cotner, S. (2019). Computer-based and bench-based undergraduate research experiences produce similar attitudinal outcomes. *CBE—Life Sciences Education*, *18*(10), 1–11. https://doi.org/10.1187/cbe.18-07-0112.
Korfiatis, K. (2018). Ecology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research*, *issues*, *and trends* (pp. 153–163). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-13/ecology-konstantinos-korfiatis?context=ubx&refId=877eb94c-1bd3-4d06-8ee3-ae38a5d603c4 (accessed on 22 January 2026).
Kulshreshtha, P., Gupta, S., Shaikh, R., Aggarwal, D., Sharma, D., & Rahi, P. (2022). Foldscope embedded pedagogy in STEM education: A case study of SDG4 promotion in India. *Sustainability*, *14*, 13427. https://doi.org/10.3390/su142013427.
Kwiek, N. C., Halpin, M. J., Reiter, J. P., Hoeffler, L. A., & Schwartz-Bloom, R. D. (2007). Pharmacology in the high-school classroom. *Science*, *317*(5846), 1871–1872. https://doi.org/10.1126/science.1146811.
Le, T. P., Pham-Shouse, T., & Do, T. L. (2022). Education for sustainable development through curricular themes of environmental knowledge: An analysis on Vietnam's biology curriculum. In M. Öztürk (Ed.), *Educational response*, *inclusion and empowerment for SDGs in emerging economies* (pp. 83–101). Sustainable Development Goals Series. Springer. https://doi.org/10.1007/978-3-030-98962-0_6.
Leal Filho, W., Castro, P., Bacelar-Nicolau, P., Azul, A. M., & Azeiteiro, U. M. (2016). Biodiversity and education for sustainable development (ESD): Tendencies and perspectives. In P. Castro, U. M. Azeiteiro, P. Bacelar-Nicolau, W. Leal Filho, & A. M. Azul (Eds.), *Biodiversity and education for sustainable development* (pp. 1–10). Springer Nature.
Lebo, N., & Eames, C. (2015). Cultivating attitudes and trellising learning: A permaculture approach to science and sustainability education. *Australian Journal of Environmental Education*, *31*(1), 46–59. https://doi.org/10.1017/aee.2015.23.

Ledbetter, M. L. S. (2012). Vision and change in undergraduate biology education: A call to action presentation to faculty for undergraduate neuroscience. *Journal of Undergraduate Neuroscience Education*, *11*(1), A22–A26.

Lederman, N. G. (2018). Nature of scientific knowledge and scientific inquiry in biology teaching. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 216–235). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-18/nature-scientific-knowledge-scientific-inquiry-biology-teaching-norman-lederman?context=ubx&refId=9f4f410e-fadb-47a6-add9-4578f82c8985 (accessed on 22 January 2026).

Leite, L., Dourado, L., & Morgado, S. (2016). Science education through problem-based learning: A review of research focused on students. In R. Henderson (Ed.), *Problem-based learning: Perspectives, methods and challenges* (pp. 125–147, ISBN 78-1-63485-183-1). New Science Publishers.

* Linder, B., & Huang, J. (2022). Beyond structure-function: Getting at sustainability within biomimicry pedagogy. *Biomimetics*, *7*, 90. https://doi.org/10.3390/biomimetics7030090.

* Livotov, P., Mas'udah, & Sekaran, A. P. C. (2021). Learning eco-innovation from nature: An interdisciplinary approach to education in systematic environmental innovation. In *REES AAEE 2021 conference: Engineering education research capability development* (pp. 242–249). Engineers Australia. https://doi.org/10.52202/066488-0027.

López-Fernández, M. M., Hierrezuelo-Osorio, J. M., Cano-Iglesias, M. J., Franco-Mariscal, A. J. (2024, March 14–15). *Go extinct! The educational game for learning about invertebrates.* New Perspectives in Science Education—International Conference 2024, Florence, Italy. Available online: https://conference.pixel-online.net/NPSE/acceptedabstracts_scheda.php?id_abs=6358 (accessed on 22 January 2026).

Martens, P., Roorda, N., & Cörvers, R. (2010). Sustainability, science, and higher education—The need for new paradigms. *Sustainability: The Journal of Record*, *3*(5), 294–303. https://doi.org/10.1089/SUS.2010.9744.

McComas, W. F. (2018). Cell biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 48–61). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-5/cell-biology-william-mccomas?context=ubx&refId=17193de0-d568-4ded-9e30-13cc7c8ffee4 (accessed on 22 January 2026).

McSorley, M., Arkhurst, B. K., Hall, M., Zha, Y., Spyrou, I. M., Duchesneau, K., Ringania, U., & Chang, M. (2023). For graduate students to become leaders in sustainability, we must transcend disciplinary boundaries. *Elementa Science in the Anthropocene*, *11*(1), 00012. https://doi.org/10.1525/elementa.2023.00012.

* Medir, R. M., Heras, R., & Magin, C. (2016). Una propuesta evaluativa para actividades de edu-cación ambiental para la sostenibilidad [An evaluation framework for environmental education through sustainability activities]. *Educación XX1*, *19*(1), 331–355. https://doi.org/10.5944/educXX1.15589.

Mikhailova, E. A., Post, C. J., & Nelson, D. G. (2024). Integrating United Nations sustainable development goals in soil science education. *Soil Systems*, *8*, 29. https://doi.org/10.3390/soilsystems8010029.

Millstein, R. L. (2013). Environmental ethics. In K. Kampourakis (Ed.), *The philosophy of biology: A companion for educators* (pp. 723–743). Springer. https://doi.org/10.1007/978-94-007-6537-5_31.

Mintz, K., & Tal, T. (2013). Education for sustainability in higher education: A multiple-case study of three courses. *Journal of Biological Education*, *47*(3), 140–149. https://doi.org/10.1080/00219266.2013.821353.

Mirosavljević, A., Bognar, B., & Sablić, M. (2024). Case study of biology teaching practices in Croatian primary schools. *Open Education Studies*, *6*(1), 20220229. https://doi.org/10.1515/edu-2022-0229.

Mitra, M., Nagchaudhuri, A., & Xavier Henry, M. S. (2016). Sustainability in BioEnergy Academy for Teachers (BEAT): Changing perspectives and practices toward "greening" the curricula. In W. Leal Filho, & S. Nesbit (Eds.), *New developments in engineering education for sustainable development* (pp. 185–197). World Sustainability Series. Springer. https://doi.org/10.1007/978-3-319-32933-8_17.

Muñoz-Galván, M., & Padilla, K. (2024). Pedagogical content knowledge about the sustainability of high school chemistry and biology teachers. *Journal of Environmental Studies and Sciences*, *14*, 652–665. https://doi.org/10.1007/s13412-024-00919-z.

Muslu, N., & Isik, H. (2024). Enhancing preservice teachers' understanding and application of place-based socioscientific issues: A focus on renewable energy and perspective-taking. In B. Namdar, & E. Karahan (Eds.), *Socioscientific issues focused teacher education* (pp. 113–132). Contemporary Trends and Issues in Science Education, 60. Springer. https://doi.org/10.1007/978-3-031-55233-5_8.

Nehm, N. H. (2018). Evolution. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 164–177). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-14/evolution-ross-nehm?context=ubx&refId=105282fa-d7f1-4453-9a79-117b8f4e3e17 (accessed on 22 January 2026).

* Nersesian, E., Vinnikov, M., & Lee, M. J. (2021, October 10–13). *Travel kinematics in virtual reality increases learning efficiency.* IEEE Symposium on Visual Languages and Human-Centric Computing, VL/HCC, Conference Paper, St Louis, MO, USA. https://doi.org/10.1109/VL/HCC51201.2021.9576317.

Nkaizirwa, J. P., Aurah, C. M., & Nsanganwimana, F. (2023). Data collected to assess the effect of inquiry-based learning on environmental knowledge and attitudes among pre-service biology teachers in Tanzania. *Data in Brief*, *49*, 109429. https://doi.org/10.1016/j.dib.2023.109429.

O'Neill, D., Kelly, R., McCormack, O., Azevedo, N. H. A. (2024). Systematic review on education outside the classroom: Lessons for science EOC practices. *Sustainability*, *16*, 5346. https://doi.org/10.3390/su16135346.

Papageorgiou, V., Druckman, A., Kioupi, V., & Pinilla-Roncancio, M. (2024) Empowering integration of sustainability in higher education curricula. In A. McNamara, D. Mahon, V. Papageorgiou, & J. Ramdeo (Eds.), *Inspire: Learning for teaching in higher education*. Nova Publishing.

* Paulauskaite-Taraseviciene, A., Lagzdinyte-Budnike, I., Gaiziuniene, L., Sukacke, V., & Daniuseviciute-Brazaite, L. (2022). Assessing education for sustainable development in engineering study programs: A case of AI ecosystem creation. *Sustainability*, *14*(3), 1702. https://doi.org/10.3390/su14031702.

* Pessoa, P., Aboim, S., Afonso, L., Lopes, J. B., & Sa'-Pinto, X. (2024). Tasting to preserve: An educational activity to promote children's positive attitudes towards intraspecific diversity conservation. *PLoS ONE*, *19*(1), e0285649. https://doi.org/10.1371/journal.pone.0285649.

Pimdee, P. (2020). Antecedents of Thai student teacher sustainable consumption behavior. *Heliyon*, *6*, e04676. https://doi.org/10.1016/j.heliyon.2020.e04676.

Power, B. (2012). Enriching students' intellectual diet through inquiry based learning. *Libri*, *62*, 305–325. https://doi.org/10.1515/libri-2012-0024.

Prieto-Jiménez, E., López-Catalán, L., López-Catalán, B., Domínguez-Fernández, G. (2021). Sustainable development goals and education: A bibliometric mapping analysis. *Sustainability*, *13*, 2126. https://doi.org/10.3390/su13042126.

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.

Putra, N. S., Permanasari, A., Setyowati, Y., Kasmita, W., & Firda, R. (2022). Biology preservice teacher levels in sustainability awareness. *AIP Conference Proceedings*, *2468*, 060015. https://doi.org/10.1063/5.0102667.

Quinn, F., Elliott, S., Taylor, N., & Littledyke, M. (2015). Education for sustainability in primary science education. In N. Taylor, F. Quinn, & C. Eames (Eds.), *Educating for sustainability in primary schools* (pp. 91–119). Sense Publishers. https://doi.org/10.1007/978-94-6300-046-8_6.

Rasmussen K. (2017). The emergence and institutional co-determination of sustainability as a teaching topic in interdisciplinary science teacher education. *Environmental Education Research*, *23*(3), 348–364. https://doi.org/10.1080/13504622.2016.1182625.

Rehman, A., Jabran, K., & Farooq, M. (2023). Curricula transformations and alternative pedagogical approaches for sustainable agriculture and environment. *International Journal of Agriculture & Biology*, *30*, 242–252. https://doi.org/10.17957/IJAB/15.2081.

Reiss, M. J. (2018). Reproduction and sex education. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 87–98). Routledge. Available online: https://www.researchgate.net/publication/344461420_Reproduction_and_Sex_Education (accessed on 22 January 2026).

Reiss, M. J., & Kampourakis, K. (2018). Introduction. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 1–8). Routledge.

Rodríguez-Loinaz, G., Ametzaga-Arregi, I., & Palacios-Agundez, I. (2022). 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.

Rodríguez-Rey, M., Ruiz-Benito, P., Zavala, M. A., Malo, A. F., & Gómez-Sal, A. (2024). Linking research, technology, and sustainability to improve the learning of how ecological processes impact human health. In F. J. García-Peñalvo, M. L. Sein-Echaluce, & Á. Fidalgo-Blanco (Eds.), *Innovation and technologies for the digital transformation of education* (pp. 195–204). Lecture Notes in Educational Technology. Springer. https://doi.org/10.1007/978-981-97-2468-0_19.

Rozenszajn, R., & Yarden, A. (2015). Exposing biology teachers' tacit views about the knowledge that is required for teaching using the repertory grid technique. *Studies in Educational Evaluation*, *47*, 19–27. https://doi.org/10.1016/j.stueduc.2015.06.001.

Rutledge, M. L. (2008). Effectiveness of elements of a diversified instructional approach in an introductory biology course. *Bioscene*, *34*(1), 24–29.

Safitri, M., Riandi, R., Widodo, A., & Nasution, W. R. (2017). Integration of various technologies in biology learning. *Journal of Physics: Conference Series*, *895*(1), 012145. https://doi.org/10.1088/1742-6596/895/1/012145.

* Salovaara, J. J., Pietikäinen J., & Cantell, H. (2021). Perceptions of interconnected sustainability: Students' narratives bridging transition and education. *Journal of Cleaner Production*, *281*, 125336. https://doi.org/10.1016/j.jclepro.2020.125336.

Sanders, D. L., & Jenkins, D. (2018). Plant biology. In K. Kampourakis, & M. J. Reiss (Eds.), *Teaching biology in schools: Global research, issues, and trends* (pp. 124–138). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781315110158-11/plant-biology-dawn-sanders-dan-jenkins?context=ubx&refId=646bb9b3-858e-4bcd-9786-536a32370272 (accessed on 22 January 2026).

* Santhosh, M. E., Bhadra, J., Ahmad, Z., & Al-Thani, N. (2025). A meta-analysis to gauge the impact of pedagogies employed in mixed-ability high school biology classrooms. *Humanities and Social Sciences Communications*, *11*(1), 175. https://doi.org/10.1057/s41599-023-02338-x.

Schlicht-Schmälzle, R., Hill, J., Folkvord, K. A., Tharaldsen, K. B., Wargo, J., Hartmann, U., & Révai, N. (2024). *Bridging the research-practice gap in education: Initiatives from three OECD countries.* OECD Education Working Paper, 319. EDU/WKP(2024)14. OECD. Available online: https://one.oecd.org/document/EDU/WKP(2024)14/en/pdf (accessed on 22 January 2026).

Schmitt-Harsh, M., & Harsh, J. A. (2017). Engaging nonscience majors in urban ecology: Recommendations for course design. *Journal of Environmental Studies and Sciences*, *7*, 550–561. https://doi.org/10.1007/s13412-016-0410-9.

* Sebastián-López, M., & González, R. M. (2020). Mobile learning for sustainable development and environmental teacher education. *Sustainability*, *12*, 9757. https://doi.org/10.3390/su12229757.

Sherry, C. (2022). Learning from the Dirt: Initiating university food gardens as a cross-disciplinary tertiary teaching tool. *Journal of Outdoor and Environmental Education*, *25*, 199–217. https://doi.org/10.1007/s42322-022-00100-6.

Sidiropoulos, E. (2018). The personal context of student learning for sustainability: Results of a multi-university research study. *Journal of Cleaner Production*, *181*, 537–554. https://doi.org/10.1016/j.jclepro.2018.01.083.

Sterling, S. (2004). An analysis of the development of sustainability education internationally: Evolution, interpretation and transformative potential. In C. Cullingford, & J. Blewitt (Eds.), *The sustainability curriculum: The challenge for higher education* (pp. 43–62). Routledge.

Sterling, S. (2010). Learning for resilience, or the resilient learner? Towards a necessary reconciliation in a paradigm of sustainable education. *Environmental Education Research*, *16*(5–6), 511–528. https://doi.org/10.1080/13504622.2010.505427.

Sterling, S. (2013). An analysis of the development of sustainability education internationally: Evolution, interpretation and transformative potential. In C. Cullingford, & J. Blewitt (Eds.), *The sustainability curriculum: The challenge for higher education* (pp. 43–62). Routledge. Available online: https://www.taylorfrancis.com/chapters/edit/10.4324/9781849773287-5/analysis-development-sustainability-education-internationally-evolution-interpretation-transformative-potential-stephen-sterling?context=ubx&refId=13a5046a-b153-4846-bfeb-5ba4ff8c9bf3 (accessed on 22 January 2026).

Stern, P. C. (2000). Toward a coherent theory of environmentally significant behavior. *Journal of Social Issues*, *56*(3), 407–424. https://doi.org/10.1111/0022-4537.00175.

Stevens, L. L., Fehler, M., Bidwell, D., Singhal, A., & Baumeister, D. (2022). Building from the bottom up: A closer look into the teaching and learning of life's principles in biomimicry design thinking courses. *Biomimetics*, *7*, 25. https://doi.org/10.3390/biomimetics7010025.

Stover, S. K., & Mabry, M. L. (2010). Biomedical research experiences for biology majors at a small college. *Bioscene*, *36*(1), 12–19.

Streiling, S., Hörsch, C., & Rieß, W. (2021). Effects of teacher training in systems thinking on biology students—An intervention study. *Sustainability*, *13*, 7631. https://doi.org/10.3390/su13147631.

Struminger, R., Short, R. A., Zarestky, J., Vilen L., & Lawing, M. (2021). Biological field stations promote science literacy through outreach. *BioScience*, *71*, 953–963. https://doi.org/10.1093/biosci/biab057.

* Sundberg, B., Areljung, S., & Ottander, C. (2019). Opportunities for education for sustainability through multidimensional preschool science. *Nordic Studies in Science Education*, *15*(4), 358–369. https://doi.org/10.5617/nordina.6237.

Susman, K. M. (2015). *Discovery-based learning in the life sciences.* Wiley-Blackwell. https://doi.org/10.1002/9781118907399.

Suwono, H. (2019). Building the pre-service biology teachers' capability through the reconstruction of life-based learning curriculum. *Journal of Physics: Conference Series*, *1317*, 012180. https://doi.org/10.1088/1742-6596/1317/1/012180.

* Tejedor, G., & Segalas, J. (2018). Action research workshop for transdisciplinary sustainability science. *Sustainability Science*, *13*, 493–502. https://doi.org/10.1007/s11625-017-0452-2.

Thinh, M. P., Tuori, R., & Diem, H. T. T. (2024). Integrating climate change education in higher education: Insights from lecturers and students across disciplines in the Mekong Delta. *Environmental Education Research*, *31*(11), 2257–2276. https://doi.org/10.1080/13504622.2024.2413630.

Thomas, H., Ougham, H., & Sanders, D. (2022). Plant blindness and sustainability. *International Journal of Sustainability in Higher Education*, *23*(1), 41–57. https://doi.org/10.1108/IJSHE-09-2020-0335.

* Upton, R. (2021). Learning for change during the global climate crisis: Exploring the (noneconomic) impact of education for sustainability using the Eden Project as a case study. In W. Leal Filho, J. Luetz, & D. Ayal (Eds.), *Handbook of climate change management* (pp. 1–24). Springer. https://doi.org/10.1007/978-3-030-22759-3_194-1.

Vandaele, M., & Stålhammar, S. (2022). "Hope dies, action begins?" The role of hope for proactive sustainability engagement among university students. *International Journal of Sustainability in Higher Education*, *23*(8), 272–289. https://doi.org/10.1108/IJSHE-11-2021-0463.

Veena Soni, A. (2020). The role of transformation in biology science and education for supporting sustainable development goals. *Kongunadu Research Journal*, *7*(2), 85–93. https://doi.org/10.26524/krj.2020.27.

* Wamsler, C. (2020). Education for sustainability: Fostering a more conscious society and transformation towards sustainability. *International Journal of Sustainability in Higher Education*, *21*(1), 112–130. https://doi.org/10.1108/IJSHE-04-2019-0152.

Wang, Y., Wu, N., Kunze, C., Long, R., & Perlik, M. (2019). Drivers of change to mountain sustainability in the Hindu Kush Himalaya. In P. Wester, A. Mishra, A. Mukherji, & A. Bhakta Shrestha (Eds.), *The Hindu Kush Himalaya assessment*, *mountains*, *climate change*, *sustainability and people* (pp. 17–56). Springer Nature.

* Wanieck, K., Ritzinger, D., Zollfrank, C., & Jacobs S. (2020). Biomimetics: Teaching the tools of the trade. *FEBS Open Bio*, *10*(11), 2250–2267. https://doi.org/10.1002/2211-5463.12963.

Warburton, K. (2003). Deep learning and education for sustainability. *International Journal of Sustainability in Higher Education*, *4*(1), 44–56. https://doi.org/10.1108/14676370310455332.

Weber, A., Büssing, A. G., Jarzyna, R., & Fiebelkorn, F. (2020). Do German student biology teachers intend to eat sustainably? Extending the theory of planned behavior with nature relatedness and environmental concern. *Sustainability*, *12*, 4909. https://doi.org/10.3390/su12124909.

* Wieërs, G., Absil, S., Maystadt, I., Nicaise, C., Modrie, P., Sibille, F.-X., Melly, L., & Dogné, J.-M. (2024). Prescribing sustainability: Should UN sustainable development goals be part of the medical, pharmacy, and biomedical education? *Frontiers in Medicine*, *11*, 1438636. https://doi.org/10.3389/fmed.2024.1438636.

Wiek, A., Withycombe, L., & Redman, C. L. (2011). Key competencies in sustainability: A reference framework for academic program development. *Sustainability Science*, *6*, 203–218. https://doi.org/10.1007/s11625-011-0132-6.

Wolff, L.-A., Vuorenpää, S., & Sjöblom, P. (2018). Chicken raising in a diverse Finnish classroom: Multidimensional sustainability learning. *Sustainability*, *10*, 3886. https://doi.org/10.3390/su10113886.

* Wright, H. A., Ironside, J. E., & Gwynn-Jones, D. (2008). The current state of sustainability in bioscience laboratories: A statistical examination of a UK tertiary institute. *International Journal of Sustainability in Higher Education*, *9*(3), 282–294. https://doi.org/10.1108/14676370810885899.

* Wright, H. A., Ironside, J. E., & Gwynn-Jones, D. (2009). Sustainability in bioscience fieldwork: Practical information from a UK agricultural research institute. *International Journal of Sustainability in Higher Education*, *10*(1), 54–67. https://doi.org/10.1108/14676370910925253.

Yli-Panula, E., Södervik, I., Jeronen, E., & Rantala, H. (2024). Finnish primary school student teachers' systems thinking regarding sustainability in connection with reproduction, biodiversity and sustainable development. *Nordic Studies in Science Education*, *20*(2), 191–205. https://doi.org/10.5617/nordina.10385.

Yoon, S. A., Koehler-Yom, J., Anderson, E., Lin, J., & Klopfer, E. (2015). Using an adaptive expertise lens to understand the quality of teachers' classroom implementation of computer-supported reform curricula in high school science. *Research in Science & Technological Education*, *33*(2), 237–251. https://doi.org/10.1080/02635143.2015.1031099.

* Zhong, Y., & Liu, J. J. (2022, June 25–27). *How does the virtual reality work on science education: An exploratory study of emotional effects on learning.* 2022 IEEE 2nd International Conference on Educational Technology (ICET) (pp. 105–109), Beijing, China. https://doi.org/10.1109/ICET55642.2022.9944496.

* Zilberman, D., Gordon, B., Hochman, G., & Wesseler, J. (2018). Economics of sustainable development and the bioeconomy. *Applied Economic Perspectives and Policy*, *40*(1), 22–37. https://doi.org/10.1093/aepp/ppx051.

Zimmerman, H. T., & Weible, J. L. (2017). Learning in and about rural places: Connections and tensions between students' everyday experiences and environmental quality issues in their community. *Cultural Studies of Science Education*, *12*, 7–31. https://doi.org/10.1007/s11422-016-9757-1.

Zoller, U. (2015). Research-based transformative science/STEM/STES/STESEP education for "sustainability thinking": From teaching to "know" to learning to "think". *Sustainability*, *7*, 4474–4491. https://doi.org/10.3390/su7044474.

Appendix B. Technical Details of Automatic Bibliometric Clustering

This attachment explains the algorithms used for automatic bibliometric clustering in the open-source graphical application Raven-visualizer (J. Jeronen, 2024), as well as the preprocessing step for word cloud generation.

The title–abstract pairs from the BibTeX data were embedded into a high-dimensional semantic space using a pretrained machine learning model, Snowflake-arctic-embed-l (Merrick et al., 2024; Snowflake, 2024). The model is a 335M-parameter semantic vectorizer, with output dimension 1024. The model has been pretrained with English text, causing semantically similar inputs to map near each other in the high-dimensional output (semantic) space. In the analysis performed in this study, the semantic vectors were normalized to unit length, causing the vectors to be located on a 1023-dimensional hypersphere surface. This enables semantic similarity detection of texts via computing the cosine similarity between each pair of vectors. A related concept is the cosine distance, which measures the dissimilarity in an analogous manner, allowing the computation of semantic distance between two texts. The embedding is schematically illustrated in Figure A1.

We will next explain the full data processing pipeline of Raven-visualizer. For a schematic illustration, see Figure A2.

The metadata of the selected studies was entered into a BibTeX database (Patashnik & Lamport, 1985). BibTeX is a popular digital open interchange format for scholarly citations.

The metadata included the authors, year, title, and abstract of each item. This database was fed to Raven-visualizer.

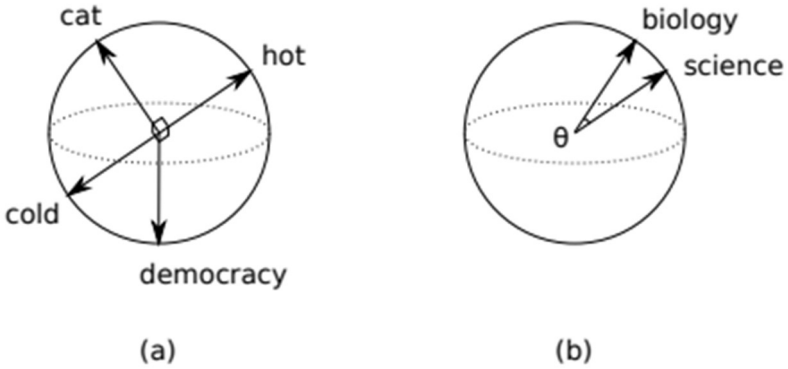


Figure A1. Semantic embeddings with normalized semantic vectors. Each concept is mapped to the 1023-dimensional surface of the unit hypersphere. (**a**) A concept ("hot") and its opposite ("cold") map to opposite directions on the hypersphere. Other unrelated concepts ("cat" and "democracy") map to orthogonal directions. (**b**) Related concepts map to directions that are close to each other. The cosine of the angle θ between the vectors measures the semantic similarity between the given pair of concepts ("biology" and "science") (figure by the authors).

When a BibTeX database is imported, Raven-visualizer initially clusters the semantic vectors in the high-dimensional space using the HDBSCAN algorithm (McInnes & Healy, 2017), with cosine distance as the pairwise distance function. A number of representative points are then automatically picked from each detected cluster. These points are used for fitting a statistical dimension reduction model from the high-dimensional space into two-dimensional space to facilitate visualization. The dimension reduction model is t-distributed stochastic neighbor embedding (t-SNE; van der Maaten & Hinton, 2008), which is a standard method that performs well for this task.

The full dataset is mapped through the fitted dimension reduction model, producing a set of points in two-dimensional space. Because t-SNE is designed to keep neighboring points together, it converts the clusters in the high-dimensional space into clusters in the two-dimensional representation. However, one must keep in mind that, similarly to when drawing a planar map of the surface of Earth (which is essentially a two-dimensional manifold in 3-space), the dimension reduction process will cause the shape of the data manifold to be distorted in the two-dimensional visualization.

The software then clusters the two-dimensional points again, using the same HDBSCAN algorithm but with different parameters, producing the final clusters used for visualization and content analysis. During development of the software, this two-stage approach was observed to produce a cleaner clustering in the two-dimensional visualization than just keeping the initial clusters from the high-dimensional space.

The HDBSCAN implementation used in this study was *scikit-learn*, version 1.6.1. In the high-dimensional space, the parameters were min_cluster_size = 5, min_samples = 1, cluster_selection_method = "leaf", metric = "cosine", and store_centers = "medoid". In the two-dimensional space, the parameters were min_cluster_size = 10, min_samples = 2, cluster_selection_method = "leaf", metric = "euclidean", and store_centers = "medoid".

The t-SNE implementation used was *OpenTSNE*, version 1.0.2. The parameters were n_components = 2, perplexity = max(16.0, N/100.0), exaggeration = 1.0, learning_rate = 10.0, metric = "cosine", n_iter = 500, and random_state = 42. Here, N = 165 is the number of items in the dataset, leading to perplexity = 1.65. The random number generator (RNG) seed was set to a fixed value for reproducibility of the dimension reduction step.

The details can be found in the Python module *raven/visualizer/importer.py* in the source code. The version of the Raven software used was 0.2.4.

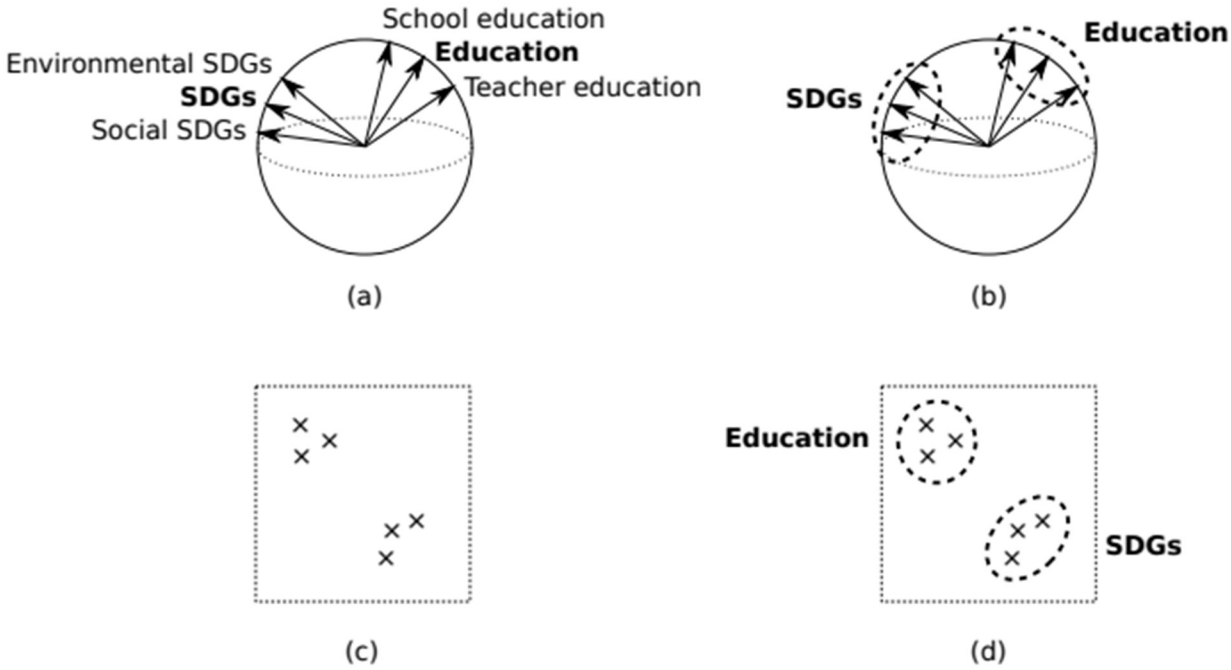


Figure A2. The data processing pipeline of Raven-visualizer. (**a**) The titles and abstracts (in this schematic illustration, represented by concepts such as "SDGs" and "Education") are embedded into a high-dimensional space with a semantic vectorizer. (**b**) The embeddings are clustered with HDBSCAN to detect the initial clusters in the high-dimensional space. (**c**) A t-SNE dimension reduction model from the high-dimensional space into two dimensions is fitted based on the initial clusters and then applied to the full dataset. In the dimension reduction, similar data points remain near each other, but each cluster may end up anywhere on the map. (**d**) The final clusters are determined by applying HDBSCAN again, now to the two-dimensional data (figure by the authors).

For producing the word cloud, Raven-visualizer automatically splits the titles and abstracts into individual words. The resulting list of words is stopworded (omitting common filler words such as "the" and "of"), lowercased (also including acronyms), and lemmatized with spaCy (Montani et al., 2023), version 3.8.5. The number of occurrences of each resulting lemmatized word in the dataset is automatically counted, and the result is fed into the "wordcloud" Python package (in this study, version 1.9.4), which generates the word cloud image.

The lemmatization process reduces each word to its stem (e.g., "thinking" becomes "think"), thereby more clearly bringing out unique concepts. The spaCy model used for lemmatization in this study was "en_core_web_sm", which is a small specialized AI model for natural language analysis of English text.

References

Abduganiev, O. I., & Abdurakhmanov, G. Z. (2020). Ecological education for the purposes sustainable development. *American Journal of Social Science and Education Innovations*, *2*, 280–284. [CrossRef]

Abeysekera, L., & Dawson, P. (2015). Motivation and cognitive load in the flipped classroom: Definition, rationale and a call for research. *Higher Education Research & Development*, *34*(1), 1–14. [CrossRef]

Aboytes, J. G., & Barth, M. (2020). Transformative learning in the field of sustainability: A systematic literature review (1999–2019). *International Journal of Sustainability in Higher Education*, *21*(5), 993–1013. [CrossRef]

Admiraal, W., Post, L., Kester, L., Louws, M., & Lockhorst, D. (2022). Learning labs in a secondary school in the Netherlands: Effects of teachers' autonomy support on student learning motivation and achievement. *Educational Studies*, *50*(5), 939–956. [CrossRef]

Aivelo, T., & Uitto, A. (2021). Factors explaining students' attitudes towards learning genetics and belief in genetic determinism. *International Journal of Science Education*, *43*(9), 1408–1425. [CrossRef]

Akinwumi, I. O. (2023). Biology education: A panacea to global environmental challenges. *European Journal of Training and Development Studies*, *10*(2), 44–56. [CrossRef]

Aksela, M., Tikkanen, G., & Kärnä, P. (2012). Mielekäs luonnontieteiden opetus: Miten tukea oppilaiden ajattelua ja ymmärtämistä? In P. Kärnä, L. Houtsonen, & T. Tähkä (Eds.), *Luonnontieteiden opetuksen kehittämishaasteita* (pp. 109–128). Koulutuksen Seurantaraportit. Opetushallitus.

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. *The Australian Educational Researcher*, *52*, 3287–3313. [CrossRef]

Aleknavičiūtė, V., Lehtinen, E., & Södervik, I. (2023). Thirty years of conceptual change research in biology—A review and meta-analysis of intervention studies. *Educational Research Review*, *41*(5), 100556. [CrossRef]

Ali, L. (2018). The design of curriculum, assessment and evaluation in higher education with constructive alignment. *Journal of Education and e-Learning Research*, *5*, 72–78. [CrossRef]

Almasri, F., Hewapathirana, G. I., Ghaddar, F., Lee, N., & Ibrahim, B. (2021). Measuring attitudes towards biology major and non-major: Effect of students' gender, group composition, and learning environment. *PLoS ONE*, *16*(5), e0251453. [CrossRef]

Alnagrat, A. J. A., Che Ismail, R., Syed Idrus, S. Z., & Abdulhafith Alfaqi, R. M. (2022). A review of extended reality (XR) technologies in the future of human education: Current trend and future opportunity. *Journal of Human Centered Technology*, *1*(2), 81–96. [CrossRef]

Annelin, A., & Boström, G. O. (2023). An assessment of key sustainability competencies: A review of scales and propositions for validation. *International Journal of Sustainability in Higher Education*, *24*(9), 53–69. [CrossRef]

Ardoin, N. M., Bowers, A. W., Wyman Roth, N., & Holthuis, N. (2018). Environmental education and K-12 student outcomes: A review and analysis of research. *The Journal of Environmental Education*, *49*(1), 1–17. [CrossRef]

Arntzen, M., Scheie, E., & Haug, B. (2025). Unveiling perceptions: How science teachers perceive sustainable development and their expectations of students' learning outcomes through environmental and sustainability education. *International Journal of Science Education*, 1–20. [CrossRef]

Atjonen, P. (2017). Arviointiosaamisen kehittäminen yleissivistävän koulun opettajien koulutuksessa. Opetussuunnitelmatarkastelun virittämiä näkemyksiä. In V. Britschgi, & J. Rautopuro (Eds.), *Kriteerit puntarissa* (pp. 132–169). Kasvatusalan tutkimuksia, 74. Suomen Kasvatustieteellinen Seura.

Avelar, A. B. A., da Silva Oliveira, K. D., & Farina, M. C. (2023). The integration of the sustainable development goals into curricula, research and partnerships in higher education. *International Review of Education*, *69*, 299–325. [CrossRef]

Àlvarez-Garcia, O., Sureda-Negre, J., & Comas-Forgas, R. (2015). Environmental education in pre-service teacher training: A literature review of existing evidence. *Journal of Teacher Education for Sustainability*, *17*, 72–85. [CrossRef]

Backman, M., Pitt, H., Marsden, T., Mehmood, A., & Mathijs, E. (2019). Experiential approaches to sustainability education: Towards learning landscapes. *International Journal of Sustainability in Higher Education*, *20*(1), 139–156. [CrossRef]

Ballard, H. L., Lindell, A. J., & Jadallah, C. C. (2024). Environmental education outcomes of community and citizen science: A systematic review of empirical research. *Environmental Education Research*, *30*(6), 1007–1040. [CrossRef]

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review*, *84*(2), 191–215. [CrossRef]

Bennett, J. A., & Saunders, C. P. (2019). A virtual tour of the cell: Impact of virtual reality on student learning and engagement in the STEM classroom. *Journal of Microbiology & Biology Education*, *20*(2). [CrossRef]

Bergmann, J., & Sams, A. (2012). *Flip YOUR classroom, reach every student in every class every day*. International Society for Technology in Education. ISBN 978-1564845603.

Bianchi, G., Pisiotis, U., & Cabrera Giraldez, M. (2022). *GreenComp—The European sustainability competence framework—JRC science for policy report* (M. Bacigalupo, & Y. Punie, Eds.). EUR 30955 EN. Publications Office of the European Union. Available online: https://data.europa.eu/doi/10.2760/13286 (accessed on 22 January 2026).

Biggers, M. (2018). Questioning questions: Elementary teachers' adaptations of investigation questions across the inquiry continuum. *Research in Science Education*, *48*, 1–28. [CrossRef]

Bleier, M. (2021). Should we bother to practice ecological responsibility? *Cultural Studies of Science Education*, *16*, 783–803. [CrossRef] [PubMed]

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). *Taxonomy of educational objectives: The classification of educational goals. Handbook I: Cognitive domain*. Longmans, Green and Co.

Boyle, A., Maguire, S., Martin, A., Milsom, C., Nash, R., Rawlinson, S., & Conchie, S. (2007). Fieldwork is good: The student perception and the affective domain. *Journal of Geography in Higher Education*, *31*(2), 299–317. [CrossRef]

Braun, T., & Dierkes, P. (2017). Connecting students to nature–how intensity of nature experience and student age influence the success of outdoor education programs. *Environmental Education Research*, *23*(7), 937–949. [CrossRef]

Brechet, C., Blanc, N., Mortier, A., & Rossi, S. (2022). Draw me a brain: The use of drawing as a tool to examine children's developing knowledge about the "black box". *Frontiers in Psychology*, *13*, 951784. [CrossRef]

Broncano, F. (2014). Daring to believe: Metacognition, epistemic agency, and reflective knowledge. In A. Fairweather (Ed.), *Virtue epistemology naturalized: Bridges between virtue epistemology and philosophy of science* (pp. 49–66). Springer International Publishing. [CrossRef]

Brondizio, E. S., Settele, J., Díaz, S., & Ngo, H. T. (Eds.). (2019). *Global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services*. IPBES Secretariat. [CrossRef]

Caeiro, S., & Simão, J. (2025). Sustainability competences and pedagogical approaches at Universidade Aberta. In R. Lozano, M. Barreiro-Gen, & F. J. Lozano (Eds.), *Developing sustainability competences through pedagogical approaches. Strategies for sustainability* (pp. 43–50). Springer. [CrossRef]

Cavadas, B., & Linhares, E. (2023). Using a problem-based learning approach to develop sustainability competencies in higher education students. In W. Leal Filho, A. M. Azul, F. Doni, & A. L. Salvia (Eds.), *Handbook of sustainability science in the future* (pp. 339–366). Springer. [CrossRef]

Cavagnetto, A. R., Premo, J., Coleman, Z., & Juergens, K. (2022). Accuracy and idea consideration: A study of small-group interaction in biology. *CBE—Life Sciences Education*, *21*(5), ar5. [CrossRef]

Chen, M., Pei, T., Jeronen, E., Wang, Z., & Xu, L. (2022). Teaching and learning methods for promoting sustainability in tourism education. *Sustainability*, *14*, 14592. [CrossRef]

Cheng, L., Ritzhaupt, A. D., & Antonenko, P. (2019). Effects of the flipped classroom instructional strategy on students' learning outcomes: A meta-analysis. *Educational Technology Research and Development*, *67*(4), 793–824. [CrossRef]

Chiu, T. K. F., Xia, Q., Zhou, X., Chai, C. S., & Cheng, M. (2023). Systematic literature review on opportunities, challenges, and future research recommendations of artificial intelligence in education. *Computers and Education: Artificial Intelligence*, *4*, 100118. [CrossRef]

Chopra, R., Joshi, A., Nagarajan, A., Fomproix, N., & Shashidhara, L. S. (2019). Climate change education across the curriculum. In W. Leal Filho, & S. L. Hemstock (Eds.), *Climate change and the role of education* (pp. 53–69). Springer.

Chowdhury, M. (2016). Emphasizing morals, values, ethics, and character education in science education and science teaching. *Malaysian Online Journal of Educational Sciences*, *4*(2), 1–16.

Christ, L., Hahn, M., Sieg, A.-K., & Dreesmann, D. C. (2022). Be(e) engaged! how students benefit from an educational citizen science project on biodiversity in their biology classes. *Sustainability*, *14*(21), 14524. [CrossRef]

Cole, M. J. (2023). Evaluative thinking. *Evaluation Journal of Australasia*, *23*(2), 70–90. [CrossRef]

Colomer, J., Serra, T., Cañabate, D., & Bubnys, R. (2020). Reflective learning in higher education: Active methodologies for transformative practices. *Sustainability*, *12*, 3827. [CrossRef]

Comer, D. R., Lenaghan, J. A., & Sengupta, K. (2015). Factors that affect students' capacity to fulfill the role of online learner. *Journal of Education for Business*, *90*, 145–155. [CrossRef]

Connors, P. K., Lanier, H. C., Erb, L. P., Varner, J., Dizney, L., Flaherty, E. A., Duggan, J. M., Yahnke, C. J., & Hanson, J. D. (2021). Connected while distant: Networking CUREs across classrooms to create community and inspire students. *Integrative and Comparative Biology*, *61*(3), 934–943. [CrossRef]

Czajkowska, A., & Ingaldi, M. (2023). Analysis of the survey results on the pro-ecological awareness of young people in the aspect of sustainable development. *Management Systems in Production Engineering*, *31*(3), 312–321. [CrossRef]

Davar, M. (2025). Effective implementation of lecture demonstration method for teaching science. *International Journal of Advanced Scientific Research*, *10*(2), 107–109. Available online: https://www.allscientificjournal.com/assets/archives/2025/vol10issue2/10038.pdf (accessed on 27 January 2025).

Dempster, E. R. (2023). What is 'powerful knowledge' in school biology? *Journal of Biological Education*, *57*(2), 245–247. [CrossRef]

Demssie, Y. N., Wesselink, R., Biemans, H. J. A., & Mulder, M. (2019). Think outside the European box: Identifying sustainability competencies for a base of the pyramid context. *Journal of Cleaner Production*, *221*, 828–838. [CrossRef]

Deringer, S. A., & Hanley, A. (2021). Virtual reality of nature can be as effective as actual nature in promoting ecological behavior. *Ecopsychology*, *13*(3), 219–226. [CrossRef]

Di Fabio, A. (2017). The psychology of sustainability and sustainable development for well-being in organizations. *Frontiers in Psychology*, *8*, 1534. [CrossRef]

Dogan, I., & Kunt, H. (2017). Determination of prospective preschool teachers' science process Ssills. *Journal of European Education*, *6*(1), 8–18. [CrossRef]

Donthu, N., Kumar, S., & Pattnaik, D. (2020). Forty-five years of Journal of Business Research: A bibliometric analysis. *Journal of Business Research*, *109*, 1–14. [CrossRef]

Dyllick, T. (2015). Responsible management education for a sustainable world. *Journal of Management Development*, *34*(1), 16–33. [CrossRef]

EC (European Commission). (2022). *Education for environmental sustainability: Policies and approaches in European Union member states. Final report*. Publications Office of the European Union. Available online: https://data.europa.eu/doi/10.2766/391 (accessed on 22 January 2026).

EC (European Commission). (2024). *Learning for sustainability in Europe. Building competences and supporting teachers and schools: Eurydice report*. European Education and Culture Executive Agency. Available online: https://data.europa.eu/doi/10.2797/81397 (accessed on 22 January 2026).

Efe, H., & Umdu Topsakal, Ü. (2025). Let's take the pulse of the classroom on sustainability! An exploratory study on student views and teacher solution suggestions regarding sustainable development goals. *Sustainability*, *17*, 5095. [CrossRef]

Elkington, J. (2007). Partnerships from cannibals with forks: The triple bottom line of 21st century business. *Environmental Quality Management, Autumn*, *8*(1), 37–51. (Original work published 1998). [CrossRef]

Ellis, A. K., & Stuen, C. J. (1998). *The interdisciplinary curriculum*. Eye On Education.

Elo, S., Kääriäinen, M., Kanste, O., Pölkki, T., Utriainen, K., & Kyngäs, H. (2014). Qualitative content analysis. *SAGE Open*, *4*(1). [CrossRef]

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *The Journal of Advanced Nursing*, *62*(1), 107–115. [CrossRef]

ElSayary, A. (2024). An introduction to interdisciplinary approach on global issues for educational reform. In A. ElSayary, & R. Olowoselu (Eds.), *Interdisciplinary approaches for educators' and learners' well-being* (pp. 3–12). Springer. [CrossRef]

Erduran, S., & Dagher, Z. R. (2014). *Reconceptualizing the nature of science for science education*. Scientific knowledge, practices and other family categories. Springer. [CrossRef]

Espinosa-Gutirrez, P.-T., Gavari-Starkie, E., Lucini-Baquero, C., & Pastrana-Huguet, J. (2025). STEAM education using natural resources in rural areas: Case study of a grouped rural school in Avila, Spain. *Sustainability*, *17*(6), 2736. [CrossRef]

EU (European Union). (2018). Council recommendation of 22 May 2018 on key competences for lifelong learning. *Official Journal of the European Union, C*, *189*, 1–13. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018H0604(01) (accessed on 13 July 2025).

Fam, D., Leimbach, T., Kelly, S., Hitchens, L., & Callen, M. (2018). Meta-considerations for planning, introducing and standardising inter and transdisciplinary learning in higher degree institutions. In D. Fam, L. Neuhauser, & P. Gibbs (Eds.), *Transdisciplinary theory, practice and education* (pp. 85–102). Springer. [CrossRef]

Faruhana, A., Asniza, I. N., & Ahmad, M. Z. (2022). An exploration into direct nature experiences (DNE) and biodiversity knowledge amongst island children. *Journal of Turkish Science Education*, *19*(2), 660–683. [CrossRef]

Fatmawati, B. (2020). Creative problem solving; implemented study in biology content. *Journal of Physics: Conference Series*, *1567*, 042079. [CrossRef]

Findley, W. G., & Woodruff, A. D. (1964). Review of taxonomy of educational objectives, Handbook II: Affective domain, by D. R. Krathwohl, B. S. Bloom, & B. B. Masia. *Journal of Educational Measurement*, *1*(2), 169–176. Available online: http://www.jstor.org/stable/1433690 (accessed on 22 January 2026).

Firinci Orman, T. (2024). Exploring youth eco-literacy through lived experiences. 'When you purchase a pair of jeans, you bear the burden of child labor in South Asia'. *The Journal of Environmental Education*, *55*(5), 363–377. [CrossRef]

Fricke, H.-J., Gathercole, C., & Skinner, A. (2015). *Monitoring education for global citizenship: A contribution to debate*. DEEEP.

Friman, H., Banner, I., Sitbon, Y., Sahar-Inbar, L., & Shaked, N. (2024). Experiential learning for sustainability: A catalyst for global change. *The Educational Administration: Theory and Practice*, *30*(5), 8508–8514. Available online: https://kuey.net/index.php/kuey/article/view/4404 (accessed on 22 January 2026).

Fu, J., Hutson, B., Thierer, K., Zhang, X., & Taylor, J. (2025). Experiential learning assessment: A dive into the literature. *Intersection: A Journal at the Intersection of Assessment and Learning*, *6*(1), 3–20. [CrossRef]

Funa, A. A., & Emberga Gabay, R. A. (2025). Bridging the gap among knowledge, attitudes, and behaviors toward sustainable development through I-STEM-PBL-ESD. *International Journal on Studies in Education*, *7*(2), 288–303. [CrossRef]

Gazoulis, I., Antonopoulos, N., Kanatas, P., Karavas, N., Bertoncelj, I., & Travlos, I. (2022). Invasive alien plant species–Raising awareness of a threat to biodiversity and ecological connectivity (EC) in the Adriatic-Ionian Region. *Diversity*, *14*(5), 387. [CrossRef]

Gericke, N. (2022). Teaching for the Anthropocene. Bildung-oriented education for sustainable development in a subject-specific curriculum. In E. Krogh, A. Qvartrup, & S. T. Graf (Eds.), *Bildung, knowledge, and global challenges in education. Didaktik and curriculum in the Anthropocene era* (1st ed., pp. 53–69). Routledge. [CrossRef]

Gericke, N., Hudson, B., Olin-Scheller, C., & Stolare, M. (2018). Powerful knowledge, transformations and the need for empirical studies across school subjects. *London Review of Education*, *16*(3), 428–444. [CrossRef]

Gericke, N., Tani, S., Newall, E., & Deng, Z. (2025). A framework for curricular analysis of powerful knowledge: Comparing school biology in England, Finland and Sweden. *Journal of Curriculum Studies*, *57*(4), 441–465. [CrossRef]

Ghafar, Z. N. (2023). The teacher-centered and the student-centered: A comparison of two approaches. *International Journal of Arts and Humanities*, *1*(1), 18–23. [CrossRef]

Gilissen, M. G. R., Knippels, M.-C. P. J., & van Joolingen, W. R. (2020). Bringing systems thinking into the classroom. *International Journal of Science Education*, *42*(8), 1253–1280. [CrossRef]

Green, C. S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current Biology*, *22*(6), 197–206. [CrossRef] [PubMed]

Green, S., Higgins, J. P. T., Alderson, P., Clarke, M., Mulrow, C. D., & Oxman, A. D. (2011). Introduction. In J. P. T. Higgins, & S. Green (Eds.), *Cochrane handbook for systematic reviews of interventions* (pp. 3–9). version 5.1.0. University of Oxford.

Hafeez, M. (2021). Project-based versus traditional lecture teaching methods. *Journal of Education And Technology*, *4*(4), 544–559. [CrossRef]

Hakkarainen, K. (2003). Progressive inquiry in a computer-supported biology class. *Journal of Research in Science Teaching*, *40*, 1072–1088. [CrossRef]

Harlen, W., Bell, D., Devés, R., Dyasi, H., de la Garza, G. F., Léna, P., Millar, R., Reiss, M., Rowell, P., & Yu, W. (2010). *Principles and big ideas of science education*. Association of Science Education. Available online: www.ase.org.uk/documents/principles-and-big-ideas-of-science-education (accessed on 22 January 2026).

Heldén, G., & Heldén, S. (2008). Students' early experiences of biodiversity and education for a sustainable future. *Nordic Studies in Science Education*, *4*(2), 123–131. [CrossRef]

Hiatt, A., Hove, A. A., Ward, J. R., Ventura, L., Boyd, A. E., Clarke, D., Horton, J. L., Murrell, Z., & Neufeld, H. S. (2021). Authentic research in the classroom increases self-efficacy and appreciation for plants in undergraduate biology students. *Integrative and Comparative Biology*, *61*(3), 969–980. [CrossRef]

Hiltunen, M., Kärkkäinen, S., & Keinonen, T. (2021). Identifying student teachers' inquiry-related questions in biology lessons. *Education Sciences*, *11*(2), 87. [CrossRef]

Holbrook, J., Rannikmäe, M., & Soobard, R. (2020). STEAM education—A transdisciplinary teaching and learning approach. In B. Akpan, & T. J. Kennedy (Eds.), *Science education in theory and practice* (pp. 465–477). Springer Texts in Education. Springer. [CrossRef]

Honra, J. R., & Monterola, S. L. C. (2025). Enhancing biology students' cognitive flexibility through problem-based learning moderated by transdisciplinary thinking. *The Journal of Educational Research*, *119*(1), 129–139. [CrossRef]

Howlett, C., Ferreira, J., & Blomfield, J. (2016). Teaching sustainable development in higher education: Building critical, reflective thinkers through an interdisciplinary approach. *International Journal of Sustainability in Higher Education*, *17*(3), 305–321. [CrossRef]

Hu, Y., Wang, M., Ren, L., & Chen, Y. (2025). Innovation and assessment system for the development of biology teaching content aligned with sustainable development goals. *Frontiers in Interdisciplinary Educational Methodology*, *2*(1), 1–16. [CrossRef]

Hubbard, K. (2024). Plant biology education: A competency-based vision for the future. *Plants People Planet*, *6*, 780–790. [CrossRef]

Hudson, B., Gericke, N., Olin-Scheller, C., & Stolare, M. (2023). Trajectories of powerful knowledge and epistemic quality: Analysing the transformations from disciplines across school subjects. *Journal of Curriculum Studies*, *55*(2), 119–137. [CrossRef]

Jahnke, I. (2012). Socio-technical learning. In N. M. Seel (Ed.), *Encyclopedia of the sciences of learning* (pp. 3141–3143). Springer Science & Business Media.

Jensen, E. L. (2025). "The name of things": Lexical ecological literacy as Bildung in environmental and sustainability education. *The Journal of Environmental Education*. [CrossRef]

Jeronen, E., Ahonen, P., & Korkeamäki, R.-L. (2022). Connections of transformative education with Bhutan's pedagogical ideas for promoting sustainability education. *Sustainability*, *14*, 163. [CrossRef]

Jeronen, E., Keinonen, T., & Kärkkäinen, S. (2024). Visioning transformative science education for sustainability. *Discourse and Communication for Sustainable Education*, *15*(1), 19–38. [CrossRef]

Jeronen, J. (2024). *Raven—Absorb scientific literature*. Available online: https://github.com/Technologicat/raven (accessed on 11 November 2025).

Kahveci, H. (2023). The positive and negative effects of teacher attitudes and behaviors on student progress. *Journal of Pedagogical Research*, *7*(1), 290–306. [CrossRef]

Kapp, K., Sivén, M., Laurén, P., Aejmelaeus, M., Virtanen, S., Katajavuori, N., & Södervik, I. (2020). Learning of laboratory skills via augmented reality-case study in pharmacy. In *EDULEARN20 proceedings* (pp. 7631–7638). IATED. [CrossRef]

Kapp, K., Sivén, M., Laurén, P., Virtanen, S., Katajavuori, N., & Södervik, I. (2022). Design and usability testing of an augmented reality (AR) environment in pharmacy education—Presenting a pilot study on comparison between AR smart glasses and a mobile device in a laboratory course. *Education Sciences*, *12*(12), 854. [CrossRef]

Kassa, M. M., Azene, M. K., Mengstie, S. M., & Ferede, M. W. (2024). Effect of multimedia and dynamic classroom integrated instruction on grade 11 students' biology academic achievements. *Helyon*, *10*(18), e37315. [CrossRef]

Kazazoglu, S. (2025). Environmental education through eco-literacy: Integrating sustainability into English language teaching. *Sustainability*, *17*, 2156. [CrossRef]

Kärnä, P., Hakonen, R., & Kuusela, J. (2012). *Luonnontieteellinen osaaminen perusopetuksen 9. luokalla 2011*. Koulutuksen seurantaraportti, 2. Juvenes Print. Opetushallitus. Tampereen yliopistopaino Oy.

Kegley, M. D., Toteva, M. T., & Wolf, J. S. (2016). Hybrids, hassles, and hiccups: Interdisciplinary perspectives on the challenges and advantages of hybrid classes. *AURCO Journal*, *22*, 111–133.

Kesler, M. (2020). *Opettaja luovan ongelmanratkaisun prosessin ohjaajana* [Ph.D. thesis, University of Helsinki]. Kasvatustieteellisiä tutkimuksia, 105. Yliopistopaino Unigrafia. Available online: http://hdl.handle.net/10138/322029 (accessed on 7 December 2025).

Kesler, M., Havu-Nuutinen, S., & Kärkkäinen, S. (2024). Ongelmanratkaisutaitojen kehittäminen biologian opetuksessa. In A. Uitto, E. Jeronen, & E. Yli-Panula (Eds.), *Biologian opetus ja tiedekasvatus kestävän tulevaisuuden edistäjinä* (pp. 171–200). Ainedidaktisia tutkimuksia, 27. Suomen ainedidaktisen tutkimusseuran julkaisuja. [CrossRef]

Kiewra, L., Powell, R. B., Stern, M. J., Hemby, T., & Browning, M. H. (2023). Is naturalness associated with positive learning outcomes during environmental education field trips? *Journal of Environmental Education*, *54*(2), 148–162. [CrossRef]

Knight, S., Buckingham Shum, S., & Littleton, K. (2014). Epistemology, assessment, pedagogy: Where learning meets analytics in the middle space. *Journal of Learning Analytics*, *1*(2), 23–47. [CrossRef]

Kolb, D. (1984). *Experimental learning. Experience as the source of learning and development*. Prentice-Hall.

Kontkanen, J., Kärkkäinen, S., Dillon, P., Hartikainen-Ahia, A., & Åhlberg, M. (2016). Collaborative processes in species identification using an internet-based taxonomic resource. *International Journal of Science Education*, *38*(1), 96–115. [CrossRef]

Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory into Practice*, *41*(4), 212–218. [CrossRef]

Kumar, V., & Kumar Choudhary, S. (2025). Reimagining scientific literacy: A textbook framework for future-focused science education. *Research in Science Education*, *55*, 1109–1127. [CrossRef]

Kurt, S. (2020). *Problem-based learning (PBL)*. Educational technology. Available online: https://educationaltechnology.net/problem-based-learning-pbl/ (accessed on 30 August 2025).

Lampert, P., Olsson, D., Hoppenreijs, J., & Gericke, N. (2025). The effectiveness of the action competence teaching approach in biodiversity education—Taking actions for insects. *International Journal of Science Education*. [CrossRef]

Landøy, A., Popa, D., & Repanovici, A. (2020). Teaching learning methods. In A. Landøy, D. Popa, & A. Repanovici (Eds.), *Collaboration in designing a pedagogical approach in information literacy* (pp. 137–161). Springer Texts in Education. Springer. [CrossRef]

Lankenau, G. R. (2018). Fostering connectedness to nature in higher education. *Environmental Education Research*, *24*(2), 230–244. [CrossRef]

Laupichler, M. C., Aster, A., Schirch, J., & Raupach, T. (2022). Artificial intelligence literacy in higher and adult education: A scoping literature review. *Computers and Education: Artificial Intelligence*, *3*, 100101. [CrossRef]

Lavie Alon, N. L., & Tal, T. (2015). Student self-reported learning outcomes of field trips: The pedagogical impact. *International Journal of Science Education*, *37*(8), 1279–1298. [CrossRef]

Lawrence, J., Morrell, L. J., & Scott, G. W. (2023). Building a competence-based model for the academic development of programme leaders. *International Journal for Academic Development*, *29*(3), 379–392. [CrossRef]

Lei, S. A., & Lei, S. Y. (2019). Evaluating benefits and drawbacks of hybrid courses: Perspectives of college instructors. *Education (Chula Vista)*, *140*(1), 1–8.

Lewinsohn, T. M., Attayde, J. L., Fonseca, C. R., Ganade, G., Jorge, L. R., Kollmann, J., Overbeck, G. E., Prado, P. I., Pillar, V. D., Popp, D., da Rocha, P. L., Silva, W. R., Spiekermann, A., & Weisser, W. W. (2015). Ecological literacy and beyond: Problem-based learning for future professionals. *Ambio*, *44*(2), 154–162. [CrossRef]

Liefländer, A. K., & Bogner, F. X. (2018). Educational impact on the relationship of environmental knowledge and attitudes. *Environmental Education Research*, *24*(4), 611–624. [CrossRef]

Liefländer, A. K., Fröhlich, G., Bogner, F. X., & Schultz, P. W. (2013). Promoting connectedness with nature through environmental education. *Environmental Education Research*, *19*(3), 370–384. [CrossRef]

Liu, Y., & Pásztor, A. (2022). Effects of problem-based learning instructional intervention on critical thinking in higher education: A meta-analysis. *Thinking Skills and Creativity*, *45*, 101069. [CrossRef]

Lovren, V. O., & Jablanovic, M. M. (2023). Bridging the gap: The affective dimension of learning outcomes in environmental primary and secondary education. *Sustainability*, *15*(8), 6370. [CrossRef]

Lozano, R., Merrill, M. Y., Sammalisto, K., Ceulemans, K., & Lozano, F. J. (2017). Connecting competences and pedagogical approaches for sustainable development in higher education: A literature review and framework proposal. *Sustainability*, *9*, 1889. [CrossRef]

Lynch, R., McCormack, O., & Hennessy, J. (2025). Exploring teachers' and students' views and experiences of field trips. *Journal of Adventure Education and Outdoor Learning*. [CrossRef]

Lyon, E. G. (2013). Learning to assess science in linguistically diverse classrooms: Tracking growth in secondary science preservice teachers' assessment expertise. *Science Education*, *97*, 442–467. [CrossRef]

McInnes, L., & Healy, J. (2017, November 18–21). *Accelerated hierarchical density based clustering*. 2017 IEEE International Conference on Data Mining Workshops (ICDMW) (pp. 33–42), New Orleans, LA, USA. [CrossRef]

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education*, *70*, 29–40. [CrossRef]

Merrick, L., Xu, D., Nuti, G., & Campos, D. (2024). Arctic-embed: Scalable, efficient, and accurate text embedding models. *arXiv*, arXiv:2405.05374. [CrossRef]

Molthan-Hill, P., Blaj-Ward, L., Mbah, M. F., & Ledley, T. S. (2022). Climate change education at universities: Relevance and strategies for every discipline. In M. Lackner, B. Sajjadi, & W. Y. Chen (Eds.), *Handbook of climate change mitigation and adaptation* (pp. 3395–3457). Springer.

Montani, I., Honnibal, M., Boyd, A., Van Landeghem, S., & Peters, H. (2023). *spaCy: Industrial-strength natural language processing in Python*. Zenodo. [CrossRef]

Morris, R., Perry, T., & Wardle, L. (2021). Formative assessment and feedback for learning in higher education: A systematic review. *Revue of Education*, *9*, e3292. [CrossRef]

Muller, J., & Young, M. (2019). Knowledge, power and powerful knowledge re-visited. *The Curriculum Journal*, *30*(2), 196–214. [CrossRef]

Murti, W., Rohman, F., Sapta Sari, M., & Ibrohim, I. (2025). Ecoliteracy competencies: A systematic literature review of domains, approaches, and impacts in education. *EURASIA Journal of Mathematics, Science and Technology Education*, *21*(8), em2677. [CrossRef] [PubMed]

Nawani, J., von Kotzebue, L., Spangler, M., & Neuhaus, B. J. (2019). Engaging students in constructing scientific explanations in biology classrooms: A lesson-design model. *Journal of Biological Education*, *53*(4), 378–389. [CrossRef]

Nazir, J., & Pedretti, E. (2016). Educators' perceptions of bringing students to environmental consciousness through engaging outdoor experiences. *Environmental Education Research*, *22*(2), 288–304. [CrossRef]

Novak, J. D. (2010). *Learning, creating, and using knowledge: Concept maps as facilitative tools in schools and corporations*. Routledge.

Odell, V., Molthan-Hill, P., Martin, S., & Sterling, S. (2019). Transformative education to address all sustainable development goals. In W. Leal Filho, A. Azul, L. Brandli, P. Özuyar, & T. Wall (Eds.), *Quality education, Encyclopedia of the UN sustainable development goals* (pp. 1–12). Springer. [CrossRef]

OECD (Organisation for Economic Co-operation and Development). (2017). *PISA 2015 assessment and analytical framework: Science, reading, mathematic, financial literacy and collaborative problem solving* (rev. ed.). PISA, OECD Publishing. [CrossRef]

OECD (Organisation for Economic Co-operation and Development). (2018). *Education at a glance 2018*. OECD Indicators. OECD Publishing. [CrossRef]

OECD (Organisation for Economic Co-operation and Development). (2019). *PISA 2018 assessment and analytical framework* (pp. 97–117). OECD Publishing. [CrossRef]

OECD (Organisation for Economic Co-operation and Development). (2023). *PISA 2025 science framework, draft*. Available online: https://pisa-framework.oecd.org/science-2025/assets/docs/PISA_2025_Science_Framework.pdf (accessed on 7 December 2025).

Oliveira, J. V., Lopes, F. S., Barboza, D. R. R., Trovao, B. M., Ramos, B. M., & Alves, N. R. R. (2019). Wild vertebrates and their representation by urban/rural students in a region of northeast Brazil. *Journal of Ethnobiology and Ethnomedicine*, *15*(1), 1. [CrossRef]

Olsson, D., Gericke, N., & Boeve-de Pauw, J. (2022). The effectiveness of education for sustainable development revisited—A longitudinal study on secondary students' action competence for sustainability. *Environmental Education Research*, *28*(3), 405–429. [CrossRef]

Osborne, J., Rafanelli, S., & Kind, P. (2018). Toward a more coherent model for science education than the crosscutting concepts of the next generation science standards: The affordances of styles of reasoning. *Journal of Research in Science Teaching*, *55*(7), 962–981. [CrossRef]

Ottander, K., & Simon, S. (2021). Learning democratic participation? Meaning-making in discussion of socioscientific issues in science education. *International Journal of Science Education*, *43*(12), 1895–1925. [CrossRef]

Ölçer-Çevik, C., & Kozaner, Ç. (2025). Building a sustainable future: Perspectives on primary school sustainability projects from teachers and pre-service teachers. *International Journal of Evaluation and Research in Education*, *14*(5), 3403–3417. [CrossRef]

Palmberg, I., Berg, I., Jeronen, E., Kärkkäinen, S., Norrgård-Sillanpää, P., Persson, C., Vilkonis, R., & Yli-Panula, E. (2015). Nordic–Baltic student teachers' identification of and interest in plant and animal species: The importance of species identification and biodiversity for sustainable development. *Journal of Science Teacher Education*, *26*(6), 549–571. [CrossRef]

Palmberg, I., Hermans, M., Jeronen, E., Kärkkäinen, S., Persson, C., & Yli-Panula, E. (2018). Nordic student teachers' views on the importance of species and species identification. *Journal of Science Teacher Education*, *29*(5), 397–419. [CrossRef]

Palmberg, I., Hofman-Bergholm, M., Jeronen, E., & Yli-Panula, E. (2017). Systems thinking for understanding sustainability? Nordic student teachers' views on the relationship between species identification, biodiversity and sustainable development. *Education Sciences*, *7*(3), 72. [CrossRef]

Palmberg, I., Jonsson, G., Jeronen, E., & Yli-Panula, E. (2016). Blivande lärares uppfattningar och förståelse av baskunskap i ekologi i Danmark, Finland och Sverige. *Nordic Studies in Science Education*, *12*(2), 197–217. [CrossRef]

Palmberg, I., Kärkkäinen, S., Jeronen, E., Yli-Panula, E., & Persson, C. (2019). Nordic student teachers' views on the most efficient teaching and learning methods for species and species identification. *Sustainability*, *11*, 5231. [CrossRef]

Patashnik, O., & Lamport, L. (1985). *BibTeX—Process bibliographies (bib files) for LaTeX or other formats*. Available online: https://www.ctan.org/pkg/bibtex (accessed on 11 November 2025).

Persano Adorno, D., Birsan, E. A., Stoica, S. F., Capatina, M., Cojocaru, C., Tzortzaki, A., Štanfelj, Z., Dinçer, Y. S., & Pizzolato, N. (2025). Sustainability as a cross-curricular link: Creative European strategies for eco-conscious environmental education. *Sustainability*, *17*, 5193. [CrossRef]

Pessoa, P., Lopes, J. B., de Lima, J., Pinto, A., Søgaard Jørgensen, P., & Sá-Pinto, X. (2024). Evolutionary literacy as a catalyst for sustainable futures: Connecting biological evolution education and education for sustainability. *Evolution: Education and Outreach*, *17*(1), 22. [CrossRef]

Pintrich, P. R. (2002). The role of metacognitive knowledge in learning, teaching, and assessing. *Theory into Practice*, *41*(4), 219–225. [CrossRef]

Prabakaran, M. (2020). Historical appropriation of epistemological values: A goal ahead for higher education. *Higher Education for the Future*, *7*(1), 67–81. [CrossRef]

Prince, M. J., & Felder, R. M. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education*, *95*(2), 123–138. [CrossRef]

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. Facing challenges in a post-truth world* (pp. 269–276). Springer.

Purwasih, D., Wilujeng, I., Wiyarsi, A., & Zakwandi, R. (2025). The socio-scientific issue based on local potential in integrated learning instruction to improve student ecological literacy. *Science & Education*. [CrossRef]

Randler, C., & Bogner, F. X. (2006). Cognitive achievements in identification skills. *Journal of Biological Education*, *40*(4), 161–165. [CrossRef]

Reen, F. J., Jump, O., McEvoy, G., McSharry, B. P., Morgan, J., Murphy, D., O'Leary, N., O'Mahony, B., Scallan, M., Walsh, C., & Supple, B. (2022). Developing student codesigned immersive virtual reality simulations for teaching of challenging concepts in molecular and cellular biology. *FEMS Microbiology Letters*, *369*(1), fnac051. [CrossRef]

Reiss, M. J., & Winterbottom, M. (2023). Teaching secondary biology. *School Science Review in Depth*, *104*(387), 19–23. Available online: https://discovery.ucl.ac.uk/id/eprint/10171259 (accessed on 22 January 2026).

Roberts, D. A. (2007). Scientific literacy/science literacy. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 729–780). Lawrence Erlbaum Associates.

Roberts, D. A., & Bybee, R. W. (2014). Scientific literacy, science literacy, and science education. In N. G. Lederman, & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. 2, pp. 545–558). Routledge.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., III, Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., . . . Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*, 472–475. [CrossRef]

Rockström, J., & Sukhdev, P. (2016). *The SDGs wedding cake*. Stockholm Resilience Centre/Stockholm University. Available online: https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html (accessed on 25 September 2025).

Rodgers, C. (2002). Defining reflection: Another look at John Dewey and reflective thinking. *The Teachers College Record*, *104*(4), 842–866. [CrossRef]

Rodriguez, M. C., & Albano, A. D. (2017). *The college instructor's guide to writing test items: Measuring student learning*. Routledge.

Saal, F. E., Downey, R. G., & Lahey, M. A. (1980). Rating the ratings: Assessing the psychometric quality of rating data. *Psychological Bulletin*, *88*(2), 413. [CrossRef]

Saira, Z. N., & Hafeez, M. (2021). A critical review on discussion and traditional teaching methods. *Psychology and Education*, *58*(1), 1871–1886.

Salonen, A., & Bardy, M. (2015). Ekososiaalinen sivistys herättää luottamusta tulevaisuuteen. *Aikuiskasvatus*, *35*(1), 4–15. [CrossRef]

Sangur, K., Zubaidah, S., & Sulisetijono. (2025). A systematic literature review of mobile learning trends in biology education over ten years. *Social Sciences & Humanities Open*, *11*, 101429. [CrossRef]

Santos, A. V., da Silva, R. S., de Souza, A. C., Vaz Rocha, E. A., da Costa Santos, L., Araújo, J. E., de Paula, M. S., Silva Pereira, N. A., & de Sousa-Baracho, I. P. (2025). Didactics and environmental education: Pedagogical workshops as a strategy for sustainability-oriented learning. *Revista Caderno Pedagógico*, *22*(9), e18184. [CrossRef]

Sass, W., Boeve-de Pauw, J., Olsson, D., Gericke, N., De Maeyer, S., & Van Petegem, P. (2020). Redefining action compe-tence: The case of sustainable development. *The Journal of Environmental Education*, *51*(4), 292–305. [CrossRef]

Savage, E., Tapics, T., Evarts, J., Wilson, J., & Tirone, S. (2015). Experiential learning for sustainability leadership in higher education. *International Journal of Sustainability in Higher Education*, *16*(5), 692–705. [CrossRef]

Sá-Pinto, X., Beniermann, A., Børsen, T., Georgiou, M., Jeffries, A., Pessoa, P., Sousa, B., & Zeidler, D. L. (Eds.). (2022). *Learning evolution through socioscientific issues*. UA Editora. [CrossRef]

Schellekens, L. H., Bok, H. G. J., de Jong, L. H., van der Schaaf, M. F., Kremer, W. D. J., & van der Vleuten, C. P. M. (2021). A scoping review on the notions of Assessment as learning (AaL), Assessment for learning (AfL), and Assessment of learning (AoL). *Studies in Educational Evaluation*, *71*, 101094. [CrossRef]

Schön, D. A. (1992). *The reflective practitioner: How professionals think in action*. Routledge. [CrossRef]

Semken, S., Geraghty Ward, E., Moosavi, S., & Chinn, P. W. U. (2017). Place-based education in geoscience: Theory, research, practice, and assessment. *Journal of Geoscience Education*, *65*(4), 542–562. [CrossRef]

Shephard, K. (2022). On the educational difference between being able and being willing. In P. Vare, N. Lausselet, & M. Rieckmann (Eds.), *Competences in education for sustainable development* (pp. 45–52). Sustainable Development Goals Series. Springer. [CrossRef]

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*(2), 4–14. [CrossRef]

Siarova, H., Sternadel, D., & Szőnyi, E. (2019). *Research for CULT committee–Science and scientific literacy as an educational challenge*. EPRS: European Parliamentary Research Service. Available online: https://policycommons.net/artifacts/1335164/research-for-cult-committee/1941452/ (accessed on 22 January 2026).

Sinakou, E., Donche, V., Boeve-de Pauw, J., & Van Petegem, P. (2019). Designing powerful learning environments in education for sustainable development: A conceptual framework. *Sustainability*, *11*(21), 5994. [CrossRef]

Singh, Y., & Suri, P. K. (2022). An empirical analysis of mobile learning app usage experience. *Technology in Society*, *68*, 101929. [CrossRef]

Sipos, Y., Battisti, B., & Grimm, K. (2008). Achieving transformative sustainability learning: Engaging heads, hands and heart. *International Journal of Sustainability in Higher Education*, *9*(1), 68–86. [CrossRef]

Sjöström, J., Economou, C., Edström, A.-M., Ekberg, J.-E., Svensson Källberg, P., Larneby, M., Liljefors Persson, B., Ryan, U., Schubert, P., Wangen, B., & Örbring, D. (2024). Knowledge contributions from different school subjects to cross-curricular didactics for bildung and sustainability. In C. Hilli, & N. Mård (Eds.), *Crossing over subject boundaries towards new horizons: Recent trends in research on crosscurricular teaching from the Nofa 9 conference* (pp. 66–91). Ainedidaktisia tutkimuksia, 25. Suomen ainedidaktinen tutkimusseura. [CrossRef]

Sjöström, J., & Eilks, I. (2018). Reconsidering different visions of scientific literacy and science education based on the concept of bildung. In Y. J. Dori, Z. R. Mevarech, & D. R. Baker (Eds.), *Cognition, metacognition, and culture in STEM education. Innovations in science education and technology* (Vol. 24, pp. 65–88). Springer. [CrossRef]

Slavin, R. E., Hurley, E. A., & Chamberlain, A. M. (2022). Cooperative learning and achievement: Theory and research. In K. R. Harris, S. Graham, T. Urdan, C. B. McCormick, & G. M. Sinatra (Eds.), *APA educational psychology handbook* (Vol. 1, pp. 253–275). American Psychological Association.

Snowflake (Snowflake, Inc.). (2024). *Snowflake's arctic-embed-l*. Available online: https://huggingface.co/Snowflake/snowflake-arctic-embed-l (accessed on 11 November 2025).

Song, H., & Cai, L. (2024). Interactive learning environment as a source of critical thinking skills for college students. *BMC Medical Education*, *24*, 270. [CrossRef] [PubMed]

Sourgiadaki, M., & Karkalakos, S. (2023). "GreenComp" as a tool for examining motivation of vocational teachers to create learning opportunities for the green transition. *SN Social Sciences*, *3*, 114. [CrossRef]

Södervik, I. (2024). Biologian ilmiöiden ymmärtäminen. In A. Uitto, E. Jeronen, & E. Yli-Panula (Eds.), *Biologian opetus ja tiedekasvatus kestävän tulevaisuuden edistäjinä* (pp. 96–130). Ainedidaktisia tutkimuksia, 27. Suomen ainedidaktisen tutkimusseuran julkaisuja. [CrossRef]

Södervik, I., Katajavuori, N., Kapp, K., Laurén, P., Aejmelaeus, M. M., & Sivén, M. (2021). Fostering performance in hands-on laboratory work with the use of mobile augmented reality (AR) glasses. *Education Sciences*, *11*(2), 816. [CrossRef]

Spaiser, V., Ranganathan, S., Bali Swain, R., & Sumpter, D. (2016). The sustainable development oxymoron: Quantifying and modelling the incompatibility of sustainable development goals. *International Journal of Sustainable Development & World Ecology*, *24*(6), 457–470. [CrossRef]

Sposab, K., & Rieckmann, M. (2024). Development of sustainability competencies in secondary school education: A scoping literature review. *Sustainability*, *16*, 10228. [CrossRef]

Springer, L., Stanne, M. E., & Donovan, S. S. (2022). Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: A meta-analysis. *Review of Educational Research*, *69*(1), 21–51. [CrossRef]

Stanny, C. (2016). Reevaluating bloom's taxonomy: What measurable verbs can and cannot say about student learning. *Education Sciences*, *6*(4), 37. [CrossRef]

Sterling, S. (2001). *Sustainable education: Re-visioning learning and change* (Vol. 6). Schumacher Briefing. Green Books.

Sterling, S., Dawson, J., & Warwick, P. (2018). Transforming sustainability education at the creative edge of the mainstream: A case study of Schumacher College. *Journal of Transformative Education*, *16*(4), 323–343. [CrossRef]

Stromie, T., & Baudier, J. (2017). Assessing student learning in hybrid courses. *New Directions for Teaching and Learning*, *149*, 37–45. [CrossRef]

Su, R., Jiang, Z., & Wei, B. (2025). Representations of nature of science in science textbooks. *Science & Education*, *34*, 585–607. [CrossRef]

Sumleth, E., & Walpuski, M. (2012). Experimental learning environments. In N. M. Seel (Ed.), *Encyclopedia of the sciences of learning* (pp. 1229–1233). Springer Science & Business Media. [CrossRef]

Swain, R. B. (2018). A critical analysis of the sustainable development goals. In W. Leal Filho (Ed.), *Handbook of sustainability science and research* (pp. 341–355). World Sustainability Series. Springer. [CrossRef]

Szczytko, R., Carrier, S. J., & Stevenson, K. T. (2018). Impacts of outdoor environmental education on teacher reports of attention, behavior, and lerning outcomes for students with emotional, cognitive, and behavioral disabilities. *Frontiers in Education*, *3*, 46. [CrossRef]

Tal, T., Levin-Peled, R., & Levy, K. S. (2019). Teacher views on inquiry-based learning: The contribution of diverse experiences in the outdoor environment. *Innovation in Education*, *1*(2), 1–17. [CrossRef]

TENK. (2019). *Human sciences in Finland. Finnish national board on research integrity TENK guidelines 2019*. Publications of the Finnish National Board on Research Integrity TENK, 3. Finnish National Board on Research Integrity TENK. Available online: https://tenk.fi/sites/default/files/2021-01/Ethical_review_in_human_sciences_2020.pdf (accessed on 22 January 2026).

Tiahrt, T., & Porter, J. C. (2016). What do I do with this flipping classroom: Ideas for effectively using class time in a flipped course. *Business Education Innovation Journal*, *8*(2), 85–91.

Tidemand, S., & Nielsen, J. A. (2017). The role of socioscientific issues in biology teaching: From the perspective of teachers. *International Journal of Science Education*, *39*(1), 44–61. [CrossRef]

Tilbury, D. (2011). *Education for sustainable development: An expert review of processes and learning*. UNESCO. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000191442 (accessed on 20 January 2026).

Toivonen, H. (2023). *Mitä tekoäly on?—100 kysymystä ja vastausta*. Kustannus-osakeyhtiö Teos.

Uitto, A., Boeve-de Pauw, J., & Saloranta, S. (2015). Participatory school experiences as facilitators for adolescents' ecological behavior. *Journal of Environmental Psychology*, *43*, 55–65. [CrossRef]

Uitto, A., Jeronen, E., & Yli-Panula, E. (2024a). Luonnontiedekasvatus ja kestävän kehityksen kasvatus biologian opetuksessa. In A. Uitto, E. Jeronen, & E. Yli-Panula (Eds.), *Biologian opetus ja tiedekasvatus kestävän tulevaisuuden edistäjinä* (pp. 66–67). Ainedidaktisia tutkimuksia, 27. Suomen ainedidaktisen tutkimusseuran julkaisuja. [CrossRef]

Uitto, A., & Saloranta, S. (2017). Subject teachers as educators for sustainability: Survey study. *Education Sciences*, *7*(1), 8. [CrossRef]

Uitto, A., Yli-Panula, E., & Jeronen, E. (2024b). Näkökulmia kestävyyttä korostavan biologian opetukseen ja arviointiin. In A. Uitto, E. Jeronen, & E. Yli-Panula (Eds.), *Biologian opetus ja tiedekasvatus kestävän tulevaisuuden edistäjinä* (pp. 79–95). Ainedidaktisia tutkimuksia, 27. Suomen ainedidaktisen tutkimusseuran julkaisuja. [CrossRef]

UN (United Nations). (2003). *Activities undertaken in implementation of Agenda 21, the programme for the implementation of Agenda 21 and the outcomes of the world summit on sustainable development*. Report of the Secretary-General. United Nations A 58/210. United Nations: General Assembly. Available online: https://digitallibrary.un.org/record/501841?v=pdf (accessed on 1 September 2025).

UN (United Nations). (2019). *Resolution adopted by the general assembly on 19 December 2019 74/233. Follow-up to the second United Nations conference on landlocked developing countries*. United Nations. Available online: https://documents.un.org/doc/undoc/gen/n19/437/29/pdf/n1943729.pdf (accessed on 2 October 2025).

UN (United Nations). (2021). *Transforming our world: The 2030 agenda for sustainable development*. Department of Economic and Social Affairs, Sustainable Development. Available online: https://sdgs.un.org/2030agenda (accessed on 9 October 2025).

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2017a). *Education for sustainable development goals: Learning objectives*. UNESCO Ebooks. [CrossRef]

UNESCO (United Nations Educational, Scientific and Cultural Organization). (2017b). *Roadmap for implementing the global action programme on education for sustainable development*. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000230514 (accessed on 23 October 2025).

Vahed, A., Walters, M. M., & Ross, A. H. A. (2023). Continuous assessment fit for purpose? Analysing themexperiences of academics from a South African university of technology. *Education Inquiry*, *14*, 267–283. [CrossRef]

Valladares, L. (2021). Scientific literacy and social transformation. *Science & Education*, *30*(3), 557−587. [CrossRef]

van der Maaten, L., & Hinton, G. (2008). Visualizing data using t-SNE. *Journal of Machine Learning Research*, *9*, 2579–2605.

van de Wetering, J., Leijten, P., Spitzer, J., & Thomaes, S. (2022). Does environmental education benefit environmental outcomes in children and adolescents? A meta-analysis. *Journal of Environmental Psychology*, *81*, 101782. [CrossRef]

Vare, P., Arro, G., de Hamer, A., Del Gobbo, G., de Vries, G., Farioli, F., KadjiBeltran, C., Kangur, M., Mayer, M., Millican, R., Nijdam, C., Réti, M., & Zachariou, A. (2019). Devising a competence-based training program for educators of sustainable development: Lessons learned. *Sustainability*, *11*, 1890. [CrossRef]

Veugen, M., Gulikers, J., & Den Brok, P. (2021). We agree on what we see: Teacher and student perceptions of formative assessment practice. *Studies in Educational Evaluation*, *70*, 101027. [CrossRef]

Villarosa, A. M. (2025). Eco-literacy awareness of pre-service science teachers: Assessment of knowledge, awareness, methics, emotion, and behaviour. *Journal of Interdisciplinary Perspectives*, *3*(7), 537–547. [CrossRef]

Vogelstein, J. T., Verstynen, T., Kording, K. P., Isik, L., Krakauer, J. W., Etienne-Cummings, R., Ogburn, E. L., Priebe, C. E., Burns, R., Kutten, K., Knierim, J. J., Potash, J. B., Hartung, T., Smirnova, L., Worley, P., Savonenko, A., Phillips, I., Miller, M. I., Vidal, R., … Yang, W. (2022). Prospective learning: Back to the future. *arXiv*, arXiv:2201.07372. [CrossRef]

Vygotsky, L. S. (1978). *Mind in society: Development of higher psychological processes*. Harvard University Press.

Wang, C.-C. (2021). The process of implementing problem-based learning in a teacher education programme: An exploratory case study. *Cogent Education*, *8*(1), 1996870. [CrossRef]

Whalen, K., & Paez, A. (2021). Student perceptions of reflection and the acquisition of higher- order thinking skills in a university sustainability course. *Journal of Geography in Higher Education*, *45*, 108–127. [CrossRef]

White, P. J., Ardoin, N. M., Eames, C., & Monroe, M. C. (2024). Agency in the Anthropocene: Education for planetary health. *Lancet Planet Health*, *8*(2), e117–e123. [CrossRef]

Wiek, A., Bernstein, M. J., Foley, R. W., Cohen, M., Forrest, N., Kuzdas, C., Kay, B., & Withycombe Keeler, L. (2016). Operationalising competencies in higher education for sustainable development. In M. Barth, G. Michelsen, M. Rieckmann, & I. Thomas (Eds.), *Handbook of higher education for sustainable development* (pp. 241–260). Routledge.

Wiek, A., & Redman, A. (2022). What do key competencies in sustainability offer and how to use them. In P. Vare, N. Lausselet, & M. Rieckmann (Eds.), *Competences in education for sustainable development* (pp. 27–34). Sustainable Development Goals Series. Springer. [CrossRef]

Wiek, A., Withycombe, L., Redman, C. L., & Banas Mills, S. (2011). Moving forward on competence in sustainability research and problem solving. *Environment: Science and Policy for Sustainable Development*, *53*(2), 3–12. [CrossRef]

Wolff, L.-A. (2022). Biodiversity education. In S. Idowu, R. Schmidpeter, N. Capaldi, L. Zu, M. Del Baldo, & R. Abreu (Eds.), *Encyclopedia of sustainable management* (pp. 1–11). Springer. [CrossRef]

Woods, C. T., Davids, K., & Araújo, D. (2024). On ecological literacy through implicated participation. *New Ideas in Psychology*, *73*, 101079. [CrossRef]

Yeon, Y.-K., Lee, B. Y., Park, S., Kim, D., Shin, Y. H., Koh, H. J., & Kim, S. W. (2025). Digital competence in geoscience fieldwork: A case study of the KMapper application. *Journal of Geography in Higher Education*. [CrossRef]

Yli-Panula, E., Banos-Conzales, I., Jeronen, E., & Matikainen, E. (2025). Student teachers' views on content knowledge of environmental issues in biological and geoscience subject matters. *Interdisciplinary Journal of Environmental and Science Education*, *21*(4), e2520. [CrossRef]

Yli-Panula, E., Jeronen, E., Inkinen, J., & Sohlman, S. (2019). Digitaaliset opetusmenetelmät biologian opetuksessa ja oppimisessa. In M. Rautiainen, & M. Tarnanen (Eds.), *Tutkimuksesta luokkahuoneisiin* (pp. 425–443). Ainedidaktisia tutkimuksia, 15. Suomen ainedidaktinen tutkimusseura. Available online: http://hdl.handle.net/10138/298542 (accessed on 22 January 2026).

Yli-Panula, E., Jeronen, E., Koskinen, S., & Mäki, S. (2022a). Finnish university students' views on climate change education and their own ability to act as climate educators. *Education Sciences*, *12*, 169. [CrossRef]

Yli-Panula, E., Jeronen, E., Koskinen, S., & Vesterkvist, S. (2020a). Biologian ja maantieteen opetuksessa käytettävät ilmastonmuutoksen opetusmenetelmät. *Ainedidaktiikka*, *4*(3), 102–124. [CrossRef]

Yli-Panula, E., Jeronen, E., & Lemmetty, P. (2020b). Teaching and learning methods in geography promoting sustainability. *Education Sciences*, *10*(1), 5. [CrossRef]

Yli-Panula, E., Jeronen, E., Lemmetty, P., & Pauna, A. (2018). Teaching methods in biology promoting biodiversity education. *Sustainability*, *10*(10), 3812. [CrossRef]

Yli-Panula, E., Jeronen, E., & Mäki, S. (2022b). School culture promoting sustainability in student teachers' views. *Sustainability*, *14*(12), 7440. [CrossRef]

Yli-Panula, E., Jeronen, E., & Pongsakdi, N. (2017a). Primary school student teachers' perceived and actual knowledge in biology. *CEPS Journal*, *7*(4), 125–146. [CrossRef]

Yli-Panula, E., Jeronen, E., Seiko-Ahlström, H., & Ruotsalainen, E. (2017b). Important biological issues for elementary pupils—A study of elementary pre-service teachers' conceptions. *Nordic Studies in Science Education*, *13*(2), 180–196. [CrossRef]

Yli-Panula, E., Jeronen, E., Vesterkvist, S., & Tolonen, P. (2021). Finnish subject student teachers' views on their social competencies at the end of their educational studies. In E. Jeronen (Ed.), *Transitioning to quality education* (pp. 63–87). Transitioning to Sustainability Series 4. MDPI.

Yli-Panula, E., Södervik, I., Jeronen, E., & Rantala, H. (2024). Finnish primary school student teachers' systems thinking regarding sustainability in connection with reproduction, biodiversity and sustainable development. *Nordic Studies in Science Education*, *20*(2), 191–205. [CrossRef]

Young, M. (2009). Education, globalization and the 'voice of knowledge'. *Journal of Education and Work*, *22*(3), 193–204. [CrossRef]

Yücel, D., & Çalışkan, İ. (2025). A comparative investigation of environmental literacy dimensions in science curricula of several countries. *Participatory Educational Research*, *12*(4), 210–228. [CrossRef]

Zeidler, D. L., Herman, B. C., & Sadler, T. D. (2019). New directions in socioscientific issues research. *Disciplinary and Interdisciplinary Science Education Research*, *1*(1), 11. [CrossRef]

Zhang, X., Jung, W., & Asari, M. (2025). Systematic review of environmental education teaching practices in schools: Trends and gaps (2015–2024). *Sustainability*, *17*, 8561. [CrossRef]

Zhao, Y., Liu, X., & Han, X. (2024). Enhancing pro-environmental behavior through nature-contact environmental education: An empirical analysis based on randomized controlled experiment design. *Frontiers in Environmental Science*, *12*, 1491780. [CrossRef]

Zhou, T., Cañabate, D., Bubnys, R., Stanikūnienė, B., & Colomer, J. (2025). Collaborative learning, cooperative learning and reflective learning to foster sustainable development: A scoping review. *Review of Education*, *13*, e70065. [CrossRef]

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