



Science Teachers as Catalysts for Environmental Literacy: A Review of Pedagogical Innovations for Sustainability in the 21st Century

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Abstract

Addressing the escalating global environmental crises necessitates environmental literacy (EL) to foster a generation capable of tackling complex sustainability challenges. Science teachers are primary change agents, imparting crucial knowledge and inspiring action. This review systematically synthesizes literature on pedagogical innovations enhancing science teachers' effectiveness in cultivating EL and sustainability education in 21st century classrooms. The article identifies and discusses five key Pedagogical approaches, including inquiry-based learning, place-based education, and technology-enhanced learning, among others. These innovations significantly improve students' cognitive, affective and psychomotor dimensions of EL, enhancing critical thinking skills, environmental problem-solving skills and heightened environmental consciousness. Successful implementation hinges on professional development, supportive policy, and resource access. The article reiterates science teachers' pivotal role in driving environmental change and outlines implications for teacher education, curriculum design and future research towards a sustainable future.

Keywords: Environmental literacy, sustainability education, science teachers, pedagogical innovations, 21st century skills, climate change education, inquiry-based learning.

1. Introduction:

The 21st century is characterized by the profound impact of anthropogenic activities on Earth's interconnected geological, biological, and atmospheric systems, leading to an unprecedented array of environmental crises (Zhou and Gu, 2024). Accelerating climate change, biodiversity collapse, widespread pollution, and resource depletion collectively pose existential threats to both ecological stability and human well-being (Iabor and Onwudinjo, 2025). Addressing these multifaceted challenges requires more than scientific understanding; it demands a deep appreciation for the intricate relationships between human societies and natural systems, reinforcing the critical imperative for environmental literacy (EL).

Environmental literacy, as defined by frameworks like the North American Association for Environmental Education extends beyond mere ecological knowledge. It encompasses a holistic understanding of environmental systems, the capacity to critically analyze environmental problems, the ability for independent judgment and action, and a profound commitment to environmental stewardship (Bey et al., 2020). EL is a multi-dimensional construct comprising:

Cognitive dimensions: Knowledge and understanding of natural systems, environmental issues, and the interconnections between human and natural systems.

Affective dimensions: Attitudes, values, concern, empathy, and motivation towards environmental protection.

Psychomotor dimensions: Skills for action, problem-solving, decision-making, effective communication, and active participation in sustainable practices.

In an era of rapid information flow and complex environmental narratives, EL is fundamental for informed decision making, responsible citizenship and the cultivation of sustainable

lifestyles at all levels. Without a populace possessing foundational EL, efforts to mitigate environmental degradation and build resilient societies will be significantly hampered.

Within formal education, science education is an indispensable domain for fostering EL. Scientific principles underlying climate change, ecosystem dynamics, and resource management form core components of science curricula, providing a rigorous foundation. Moreover, science education cultivates critical thinking, data analysis, problem-solving, and evidence-based reasoning skills directly transferable and essential for effectively addressing environmental challenges (Mafarja et al., 2025).

Science teachers are central to this educational endeavor. They are pivotal agents of change, capable of inspiring, educating, and empowering students to become environmentally literate citizens (Mittal and Bansal, 2024). Their disciplinary expertise allows them to demystify complex environmental scientific concepts, while their pedagogical skills translate abstract knowledge into tangible, real world relevance. Their role extends to fostering scientific inquiry into environmental problems, facilitating ethical discussions, and guiding students towards proactive engagement and sustainable actions. In essence, science teachers act as catalysts, igniting curiosity, fostering critical awareness, and cultivating the skills and attitudes necessary for environmental stewardship.

Despite this pivotal role, science teachers often face significant barriers in effectively integrating EL into their instruction. These challenges include curriculum constraints prioritizing traditional content, inadequate professional development in environmental education pedagogies, limited access to resources and outdoor learning opportunities, and the pressure of standardized testing which can marginalize interdisciplinary and experiential learning (Mngomezulu and Ramaila, 2025). Addressing these barriers requires a concerted effort to support teachers with innovative pedagogical approaches and necessary professional backing.

2. Scope and Purpose of the Review

Recognizing both the urgency of environmental literacy and the pivotal yet often constrained role of science teachers, this review systematically synthesizes emerging pedagogical innovations aimed at equipping teachers to promote environmental literacy and sustainability education in the 21st century. Specifically, this article seeks to:

1. Identify and describe key pedagogical innovations demonstrating effectiveness in cultivating various dimensions of environmental literacy among students.
2. Analyze how these innovations leverage the unique position of science education to engage students with complex environmental issues.
3. Discuss the enablers and challenges faced by science teachers in implementing these innovative pedagogies.
4. Provide implications for teacher education, curriculum development, and policy to support science teachers as catalysts for environmental literacy.

Through a critical analysis of relevant research, this review aims to provide an overview of best practices and emerging trends to inform researchers, educators and policymakers dedicated to advancing environmental literacy for sustainability.

3. **Conceptual Framework: Environmental Literacy and Sustainability Education**

The concept of environmental literacy has evolved significantly since its inception, broadening to reflect the increasing complexity of environmental challenges. While early conceptualizations often focused on ecological knowledge (McBride et al., 2013), contemporary definitions, influenced by organizations like the North American Association for Environmental Education (NAAEE) (Simmons, 1995), embrace a more comprehensive set of attributes. Today, EL is understood as a multi-dimensional construct encompassing cognitive, affective, and psychomotor domains.

1. **Cognitive Dimension:** Involves foundational knowledge of natural systems (e.g., ecology, climate science), understanding environmental issues (causes, impacts, solutions), and interconnections between human societies and the environment. It also includes critical analysis skills and problem identification.
2. **Affective Dimension:** Relates to attitudes, values, beliefs, emotions, concern, empathy, and responsibility towards the environment. Fostering a personal connection to nature and an ethical stance are crucial.
3. **Psychomotor Dimension:** Encompasses practical skills and behaviors for environmental action, including problem-solving, sustainable decision-making, effective communication, and active participation in civic processes and personal/collective actions.

The relationship between scientific literacy and environmental literacy is particularly salient in science education. Scientific literacy, defined as the knowledge and understanding of scientific concepts for informed decision making and civic engagement (Yacoubian, 2018), provides the essential grounding for EL. An environmentally literate individual must first be scientifically literate to critically evaluate claims, understand scientific evidence and appreciate the scientific basis of environmental problems and solutions. Hence, science teachers are uniquely positioned to build this synergistic foundation.

Environmental literacy is intrinsically linked to Education for Sustainable Development (ESD). Spearheaded by UNESCO, ESD empowers learners to make informed decisions and take responsible actions for environmental integrity, economic viability, and a just society (Nwosu, 2024). The key connections between EL and ESD include:

1. **Holistic Perspective:** Both advocate for understanding ecological, social, and economic systems as interconnected.
2. **Action Oriented:** Both emphasize developing skills, values and attitudes that lead to positive change.
3. **Future Oriented:** Both aim to ensure future generations' well-being and planetary capacity.

By cultivating EL, science teachers significantly contribute to broader ESD goals and equip students with crucial 21st century skills such as critical thinking, problem solving, creativity, collaboration, communication, and global awareness (Kioupi and Voulvoulis, 2019).

4. Theoretical Frameworks Underpinning Effective EL Pedagogy

Effective pedagogical approaches for fostering environmental literacy and sustainability are frequently grounded in educational theories emphasizing active, experiential, and socially constructed learning:

1. **Constructivism** (Piaget, 1950; Vygotsky, 1997): Posits that learners actively construct knowledge through experience and reflection. In EL, this means students investigate environmental phenomena rather than passively receiving facts, underpinning inquiry-based learning.
2. **Socio-cultural Theory** (Vygotsky, 1997): Highlights the importance of social interaction and cultural context. For EL, this translates to collaborative learning, community engagement, and discussions that build shared understanding of environmental issues within social contexts.
3. **Experiential Learning** (Dewey, 1938; Kolb, 1984): Emphasizes learning by doing and reflecting on direct experiences. This is powerful for EL through direct interaction with nature (e.g., field trips, citizen science) and hands-on problem-solving, deepening understanding and fostering personal connection.
4. **Place-Based Education** (Sobel, 2004): Explicitly connects learning to the local environment, culture, and community. Drawing on constructivist and experiential principles, it grounds abstract concepts in tangible reality, making learning relevant and fostering stewardship for one's place.

These frameworks collectively highlight the need for EL pedagogies that move beyond traditional didactic instruction, advocating for active, engaging and contextually rich learning experiences that empower students to critically analyze, connect emotionally, and act responsibly towards the environment.

5. Methodological Approach

5.1 Search Strategy and Inclusion Criteria

A systematic search strategy was employed across reputable academic databases: Web of Science (Core Collection), Scopus, ERIC, PsycINFO and Google Scholar (for broader coverage). Boolean operators combined keywords such as ("environmental literacy" OR "sustainability education" OR "climate change education") AND ("science teacher" OR "science pedagogy") AND ("innovative pedagogy" OR "inquiry-based learning" OR "place-based learning" OR "technology enhanced learning" OR "interdisciplinary teaching"). The primary timeframe for article inclusion was 2000 to 2025, chosen to reflect 21st century pedagogical evolution and sustainability awareness. Seminal works predating 2000 were considered for foundational theories.

Inclusion criteria focused on: 1) Peer-reviewed journal articles in English; 2) Studies explicitly addressing pedagogical innovations by science teachers (K-12 and tertiary) to foster EL or sustainability education; 3) Empirical studies, reviews, theoretical frameworks providing insights into effective practices; 4) Articles demonstrating clear links between interventions and EL outcomes (knowledge, attitudes, skills, behaviors) or teacher professional development.

Exclusion criteria included non-peer-reviewed publications, studies focused solely on environmental science content without pedagogical implications, or those lacking sufficient methodological detail.

5.2 Data Extraction and Synthesis

Initial search results underwent title and abstract screening. Full-text articles were then meticulously reviewed. For each included article, systematic data extraction coded: bibliographic details, study type, context, specific pedagogical innovations, teacher's role, reported student outcomes (cognitive, affective, psychomotor EL dimensions), methodology (for empirical studies), identified challenges/enablers, and key takeaways. The extracted data was synthesized using a thematic analysis approach (Braun & Clarke, 2006), involving familiarization, initial coding, grouping codes into overarching themes, reviewing, defining and naming themes, and finally weaving them into a coherent narrative. This rigorous methodology ensured systematic identification of robust patterns and insights into effective EL pedagogies.

6. Pedagogical Innovations for Fostering Environmental Literacy

The literature reveals a rich array of pedagogical innovations empowering science teachers to cultivate environmental literacy and sustainability competencies. These approaches move beyond traditional models, emphasizing active learning, real world engagement and higher order thinking.

Table 1: Key Pedagogical Innovations and Their Impact on Environmental Literacy

Pedagogical Innovation (Core Examples)	Description of Approach	Key Impacts on Environmental Literacy Dimensions (Cognitive, Affective, Psychomotor)
Inquiry-Based & Problem-Based Learning (IBL/PBL) (e.g., Water quality testing, local pollution investigations)	Student-driven exploration, question formulation, evidence gathering, and collaborative problem-solving focused on authentic environmental issues.	Cognitive: Enhances scientific reasoning, data interpretation, critical thinking, and deep understanding of environmental systems. Affective: Fosters a sense of ownership, increased motivation for finding solutions, and personal relevance. Psychomotor: Develops practical problem-solving skills.
Place-Based & Community-Engaged Learning (e.g., Field trips, school gardens, ecological surveys)	Learning is grounded in the local environment, culture, and community, involving students in real world projects that address local environmental needs.	Affective: Cultivates a strong sense of place, empathy for local ecosystems, personal connection to issues, and civic responsibility. Cognitive: Provides rich, contextualized learning, making

Technology-Enhanced Learning

(e.g., GIS, remote sensing, VR/AR simulations)

Integrates digital tools and platforms for advanced data analysis, visualization, simulation, and global collaboration to create dynamic and interactive learning experiences.

Interdisciplinary & Trans-disciplinary Approaches

(e.g., Zero-waste school projects, Indigenous knowledge integration)

Integrates concepts, methods, and perspectives from multiple academic disciplines (e.g., science, economics, and ethics) and involves non-academic stakeholders in co-creating knowledge and solutions.

Affective & Values-Based Education

(e.g., Environmental storytelling, ethical dilemma discussions)

Focuses on cultivating environmental ethics, empathy, and a sense of personal responsibility by exploring students' emotions, values, and relationship with the natural world.

scientific concepts tangible and applicable.

Psychomotor: Encourages hands-on participation in conservation and community projects.

Cognitive: Improves data literacy, access to vast real world data, sophisticated analysis, and exploration of complex environmental systems.

Affective: Immersive experiences can evoke empathy and a sense of urgency regarding environmental challenges.

Psychomotor: Develops essential 21st-century digital competencies for environmental stewardship (e.g., data mapping, digital modeling).

Cognitive: Fosters a holistic understanding of complex environmental issues, revealing social, economic, and ethical dimensions beyond purely scientific facts; enhances critical thinking from multiple perspectives.

Affective: Promotes empathy and a broader sense of global citizenship by exposing students to diverse cultural responses.

Psychomotor: Strengthens collaborative problem-solving skills through engagement with real-world stakeholders, bridging theory and practice.

Affective: Primarily targets this domain, fostering deep-seated values, a sense of care, and intrinsic motivation to act sustainably; helps students process emotions related to environmental issues.

Cognitive: Develops reasoned ethical positions.

Psychomotor: Strengthens internal drivers for sustained responsible behaviors.

<p>Climate Change Education Specific Innovations (e.g., Climate models, addressing misconceptions)</p>	<p>Targeted pedagogies addressing the complexity, implications, strategies, adaptation, principles of climate change specifically related to climate change.</p>	<p>Cognitive: Builds foundational climate literacy, enabling understanding of climate science, scientific data interpretation, and critical societal evaluation of information.</p> <p>Affective: Fosters a sense of urgency and responsibility and principles of climate justice regarding climate action.</p> <p>Psychomotor: Equips students with knowledge and skills to advocate for and implement climate solutions.</p>
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These innovations collectively provide a powerful instrument for science teachers, transforming classrooms into dynamic hubs for cultivating environmentally literate and sustainably minded citizens by moving beyond traditional lectures towards active, experiential, and socially relevant learning.

7. The Role of the Science Teacher: Enablers and Challenges

The effective implementation of the pedagogical innovations discussed hinges critically on the science teacher. Their knowledge, skills, attitudes, and the broader support systems are paramount for successfully fostering environmental literacy. This section explores the key enablers that empower teachers and the persistent challenges they face.

Table 2: Enablers and Challenges for Science Teachers in Fostering Environmental Literacy

Enablers (Factors Supporting Teachers)	Challenges (Factors Hindering Teachers)
<p>High-Quality Professional Development (PD):</p> <ul style="list-style-type: none"> - Experiential workshops, field investigations, citizen science. - Collaborative learning networks and communities of practice. - Mentoring programs and sustained, iterative training (beyond one-off workshops). 	<p>Curriculum Constraints & Time Pressure: Overcrowded curricula and pressure to cover extensive content for standardized tests.</p> <p>Lack of Resources: Insufficient teaching materials, adequate technology (e.g., GIS software, data loggers), funding for field trips, or outdoor learning spaces.</p> <p>Teacher Beliefs & Attitudes: Skepticism about the relevance of environmental education, perceiving it as outside their core science mandate, or feeling ill-equipped to address its socio-political dimensions.</p> <p>Lack of Institutional Support: Insufficient support from school administration, lack of recognition for environmental education efforts, or resistance from colleagues.</p>

- PD focused on curriculum adaptation and development aligned with EL goals.

Gaps in Pre-service Teacher Preparation:

Inadequate initial training in specific EL content, pedagogical skills (e.g., inquiry-based, place-based, values-based), or effective use of environmental technologies.

Outcomes of Effective PD: Enhanced content knowledge, increased pedagogical confidence, higher self-efficacy in teaching environmental topics, and a shift towards being a facilitator of environmental learning.

Ultimately, science teachers are at the forefront of this crucial educational endeavor. Empowering them with robust professional development, supportive policy frameworks, accessible resources, and strong institutional backing is not merely beneficial but essential for leveraging their catalytic potential in cultivating a generation of environmentally literate citizens.

8. Discussion:

This review unequivocally reaffirms the critical role of science teachers as catalysts for environmental literacy (EL) in the 21st century. The synthesis of literature reveals a compelling case for adopting several innovative pedagogical approaches that collectively strengthen the cognitive, affective and psychomotor dimensions of EL among students. The most impactful pedagogical innovations identified, as summarized in Table 1, include Inquiry-Based and Problem-Based Learning, Place-Based and Community-Engaged Learning, Technology-Enhanced Learning, Interdisciplinary and Trans-disciplinary Approaches, Affective and Values-Based Education, and Climate Change Education Specific Innovations.

Common threads across these effective practices include a significant shift towards student-centered learning, a strong emphasis on real world relevance, the promotion of active and experiential engagement and the cultivation of essential 21st century skills such as critical thinking, collaboration and communication. These pedagogies transcend the traditional transmission of facts, empowering students as active learners and informed decision makers regarding complex environmental issues.

Crucially, the success of these innovations is inextricably linked to the science teacher. Their role has evolved from a purveyor of scientific facts to a facilitator, mentor and guide who enable students to investigate, question, reflect and act. As highlighted in Table 2, the ability of science teachers to adopt and adapt these innovative approaches is paramount, making their ongoing professional development and the supportive ecosystems around them absolutely central to the agenda of fostering environmental literacy. While significant progress has been made, persistent barriers necessitate continued strategic interventions at policy, institutional and individual teacher levels.

9. Implications for Theory and Practice:

The findings of this review carry significant implications across various levels of the educational ecosystem, aiming to bolster the role of science teachers as EL catalysts.

For Teacher Education:

1. **Curriculum Integration:** Pre-service programs must integrate robust EL components beyond basic environmental science content. This includes specific pedagogical strategies for EL, such as inquiry-based design, place-based curriculum development, effective use of environmental technologies, and facilitating interdisciplinary and values based discussions.
2. **Sustained Professional Development (PD):** In-service PD must be sustained, experiential, and collaborative, moving beyond one-off workshops. Teachers require ongoing opportunities to deepen content knowledge in emerging environmental topics such as climate justice, refine pedagogical skills, share best practices and receive mentorship. PD should empower teachers to adapt global environmental issues to local contexts.
3. **Building Self-Efficacy:** Teacher education programs should prioritize building science teachers' self-efficacy and confidence in teaching environmental issues, including potentially controversial topics, by providing tools for evidence-based discussion and classroom management strategies.

For Curriculum Developers:

1. **Flexibility and Cross Curricular Connections:** Curricula should be designed with inherent flexibility and explicit cross curricular connections that actively encourage EL integration, rather than viewing it as an optional add-on. Environmental themes should be woven throughout science standards, demonstrating natural connections across biology, chemistry, physics, and Earth science.
2. **Rich Modules:** Develop rich, open-ended environmental inquiry modules and problem-based scenarios that teachers can easily adapt to their local contexts.
3. **Resource Integration:** Include resources and examples that leverage technology and promote outdoor, experiential learning opportunities.
4. **Inclusive Knowledge Systems:** Recognize and integrate Indigenous ecological knowledge and diverse cultural perspectives on sustainability within the curriculum.

For Educational Policy Makers:

1. **Policy Mandates:** Policies need to explicitly mandate or strongly encourage environmental literacy and education for sustainable development across all levels of education, with clear learning outcomes.
2. **Resource Allocation:** Allocate adequate funding and resources for teacher professional development in EL, robust curriculum materials, authentic field experiences and technology infrastructure to support innovative pedagogies.
3. **Assessment Reform:** Evolve assessment frameworks to measure not only factual recall but also students' ability to apply scientific knowledge to solve environmental problems, demonstrate critical thinking, and exhibit environmentally responsible attitudes and behaviors.
4. **Collaboration Promotion:** Policies should actively promote interdisciplinary collaboration within schools and foster partnerships with local environmental organizations and scientific institutions.

For Classroom Teachers:

1. **Embrace Facilitator Role:** Transition from purely didactic instruction to embracing the role of a facilitator and guide.
2. **Seek PD:** Actively seek out professional development opportunities related to environmental literacy and sustainability.
3. **Localize Learning:** Look for opportunities to connect scientific concepts to local environmental issues, utilizing the schoolyard and local community as a living laboratory.
4. **Strategic Technology Use:** Integrate technology strategically to enhance student engagement with environmental data and complex systems.
5. **Foster Open Dialogue:** Create an open and respectful classroom environment where students can critically discuss environmental dilemmas and express their feelings about sustainability challenges.

10. Conclusion:

This review unequivocally reaffirms the indispensable role of science teachers as catalysts for environmental literacy. In an era of profound ecological crises, the next generation's capacity to understand and respond to environmental degradation significantly hinges on the quality of environmental education received. Science teachers, with their disciplinary expertise and innovative pedagogical approaches are uniquely positioned to ignite environmental consciousness, cultivate critical thinking skills and foster the skills and values necessary for a sustainable future. Their ability to translate complex science into actionable knowledge and inspire responsibility is central to the societal shift towards sustainability. Future research should also explore teacher well-being and mental health when addressing sustainability issues, an emerging and critical area

11. Future Directions for Research

To further strengthen the role of science teachers in fostering environmental literacy, several areas warrant focused future research:

1. **Longitudinal Studies:** More long-term research is needed to track the sustained impact of specific pedagogical innovations on students' environmental knowledge, attitudes, behaviors, and career choices beyond their schooling years. This will provide robust evidence of enduring impact.
2. **Teacher Efficacy and Self-Beliefs:** Research should delve deeper into the factors influencing science teachers' self-efficacy in teaching environmental topics, including climate change, and how professional development can most effectively bolster their confidence and willingness to engage with these complex and often controversial issues.
3. **Role of Emerging Technologies (AI, Data Science):** Explore how rapidly evolving technologies like Artificial Intelligence, advanced data analytics, and sophisticated simulations can be integrated into EL pedagogies to provide even more immersive, personalized, and data-rich learning experiences, while also considering ethical implications.
4. **Comparative Studies:** Conduct comparative research across different national and cultural contexts to understand how diverse educational systems, curricula, and societal values influence the implementation and effectiveness of EL pedagogies. This can reveal transferable best practices and context-specific challenges.

5. Assessment of Affective/Psychomotor Domains: Further research is needed on developing robust and reliable assessment methods for the affective and psychomotor dimensions of EL, beyond traditional cognitive measures.

12. A Call to Action

The urgency of the environmental crisis demands an immediate and sustained commitment to empowering science teachers. Investing in their professional development, providing supportive policy frameworks, ensuring access to necessary resources, and fostering a culture of interdisciplinary collaboration are not optional luxuries but fundamental necessities. By embracing the pedagogical innovations discussed in this review and by continuously supporting the dedicated science teachers who implement them, we can collectively equip students with the environmental literacy they need to become responsible global citizens and active participants in shaping a more sustainable, equitable and resilient world. The time for action is now; the catalysts are in our classrooms.

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