Dialogues in Humanities and Social Sciences
2026, VOL. 4, NO. 2, 79-98
ISSN (P): 3078-8838; ISSN (O): 3078-8846
https://doi.org/10.71261/dhss/4.2.79

STEM Education for Climate Change Learning in Secondary Schools: A Review of Pedagogical Approaches, Competencies, and Educational Outcomes

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ABSTRACT

Climate change is a complex scientific, technological, environmental, and societal challenge that requires education beyond factual knowledge transmission. This narrative review examines three questions: which STEM-oriented pedagogical approaches support climate change learning in secondary schools; which climate-related, STEM, and sustainability competencies are developed; and which educational outcomes and assessment strategies are reported. The reviewed literature identifies inquiry-based learning, project- and problem-based learning, socio-scientific issue approaches, engineering and design-based learning, place-based learning, and technology- and data-enhanced learning as meaningful approaches to climate change education. These approaches can foster climate and scientific literacy, systems thinking, critical thinking, problem solving, data literacy, collaboration, decision making, and action competence. Evidence is strongest for improvements in climate-related knowledge and conceptual understanding, while gains in motivation, attitudes, and engagement are also reported. Evidence concerning sustained behavioural and collective climate action remains more limited and heterogeneous. The review therefore highlights that the educational value of STEM depends not simply on incorporating STEM activities, but on integrating disciplinary knowledge with authentic climate problems, empirical evidence, quantitative analysis, design processes, and appropriate assessment. Based on the synthesis, a conceptual STEM Climate Learning Pathway is proposed, linking authentic climate challenges with pedagogical processes, competency development, educational outcomes, and the potential for informed climate action.

ARTICLE HISTORY
Received 28 June 2026
Revised 30 July 2026
Accepted 12 August 2026
Published 15 August 2026

KEYWORDS
Climate change education, STEM education, secondary schools, sustainability competencies, climate literacy.

Introduction

Climate change is a multidimensional challenge that extends beyond the natural sciences to technology, infrastructure, economics, public health, environmental management, and everyday decision making. Consequently, climate change education requires more than the acquisition of factual knowledge about greenhouse gases, global warming, or climate variability. Students need opportunities to interpret scientific evidence, understand interconnected systems, evaluate possible solutions, work with data, and make informed decisions in situations involving environmental and societal uncertainty. (Aeschbach et al., 2025; Martin et al., 2025)

Secondary schools have an important role in developing these capacities because students at this level can engage with increasingly complex scientific concepts, quantitative information, technological systems, and socio-scientific issues. However, climate change is still frequently

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addressed either as scientific content or as an environmental and behavioural issue, with insufficient integration between scientific understanding, technological applications, problem solving, and decision making. This creates a need for educational approaches that can connect disciplinary knowledge with authentic climate-related problems. (Martin et al., 2025; Thibaut et al., 2018)

Integrated Science, Technology, Engineering, and Mathematics (STEM) education provides a potentially suitable framework for addressing this challenge. Integrated STEM approaches emphasise connections among disciplinary knowledge, authentic problems, inquiry, design, collaboration, and the application of knowledge to practical situations. In their systematic review of instructional practices in secondary education, Thibaut et al. (2018), *Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education*, identified problem-centred learning, inquiry, design, collaboration, and disciplinary integration as important characteristics of integrated STEM education. These characteristics are particularly relevant to climate change because climate-related problems commonly require scientific investigation, quantitative analysis, technological tools, engineering solutions, and evaluation of social and environmental consequences.

The relationship between STEM education and sustainability competencies has also received increasing attention. Quintana-Cifuentes et al. (2019), *Sustainability Competencies in STEM Education at Secondary Schools: A Systematized Literature Review*, highlighted the potential of STEM learning to support competencies relevant to sustainability challenges. More recently, Sposab and Rieckmann (2024), *Development of Sustainability Competencies in Secondary School Education: A Scoping Literature Review*, identified competency dimensions such as systems thinking, critical thinking, problem solving, collaboration, and action-oriented capacities across secondary education. These competencies are particularly important for climate change learning because climate-related challenges involve interactions among environmental, technological, economic, and social systems.

Empirical studies provide evidence of several ways in which STEM-oriented pedagogies can be applied to climate change learning. Brumann et al. (2022), *Inquiry-Based Learning on Climate Change in Upper Secondary Education: A Design-Based Approach*, demonstrated the potential of inquiry-based learning to position climate change as an object of investigation rather than simply as content to be transmitted. Choi et al. (2021), *The Impacts of a Climate Change SSI-STEAM Program on Junior High School Students' Climate Literacy*, similarly demonstrated the potential of integrating climate change with socio-scientific issues and STEAM learning to support climate literacy among junior high school students. Kundariati et al. (2025), *Navigating Climate Change Education: A Problem-Oriented Project-Based Learning in Secondary Schools*, further illustrates how project-based learning can engage students with authentic climate-related problems and possible responses.

Place-based and empirical approaches provide additional opportunities to connect climate science with students' immediate environments. Hernandez et al. (2022), *Place-Based Education in High School Science: Situating Energy and Climate Change in Students' Communities*, emphasised the value of situating climate and energy learning within students' local communities. Kumar et al. (2023), *Using Empirical Science Education in Schools to Improve Climate Change Literacy*, likewise demonstrated the value of empirical investigation for developing students' understanding of climate-related phenomena. Data-intensive approaches are also increasingly relevant. Thacker (2024), *Supporting Secondary Students' Climate Change Learning and Motivation Using Novel Data and Data Visualizations*, highlights the potential of data and visualisation to support climate change learning and student motivation.

Despite these developments, evidence concerning STEM-based climate change learning remains distributed across several research traditions, including climate change education, science education, integrated STEM, sustainability education, and socio-scientific issues research. Existing reviews have generally focused on one of these areas rather than examining the connections among STEM pedagogy, competency development, and educational outcomes. A recent meta-analysis by Aeschbach et al. (2025), *Effectiveness of Climate Change Education—A Meta-Analysis*, provides broader evidence concerning the effectiveness of climate change education, while Chen et al. (2026), *The Effect of School Science Education on Students' Climate Literacy: A Three-Level Meta-Analysis*, further examines the effects of school science education on climate literacy. Tijani and Adeduyigbe (2026), *Systematic Review of Science Education Approaches to Climate Change Education and Sustainable Development Goal 13*, synthesised research on science education approaches to climate change and SDG 13. These studies provide important foundations but also indicate the need to examine more specifically how STEM-oriented learning processes contribute to different types of competencies and educational outcomes.

An important issue emerging from this literature is the distinction between knowledge acquisition and climate action. Improvements in climate-related knowledge and conceptual understanding are relatively well represented in the literature, whereas evidence concerning sustained behavioural change, collective action, or students' capacity to apply learning to real-world climate decisions appears more heterogeneous. This distinction suggests that the effectiveness of STEM-based climate education should not be evaluated solely through conventional knowledge tests. Assessment may also need to consider systems thinking, problem solving, data interpretation, design competence, collaboration, decision making, motivation, and action-oriented outcomes. (Aeschbach et al., 2025; Chen et al., 2026)

Against this background, the present narrative review examines how STEM-oriented pedagogical approaches have been used to support climate change learning in secondary schools and how these approaches relate to competency development and educational outcomes. The review addresses three research questions: **RQ1.** Which STEM-based pedagogical approaches have been used to support climate change learning in secondary schools? **RQ2.** Which climate-related, STEM, and sustainability competencies are developed through these approaches? **RQ3.** What educational outcomes and assessment approaches have been reported in the literature? By addressing these questions together, the review aims to provide a more integrated understanding of the contribution of STEM education to climate change learning. It further proposes a conceptual STEM Climate Learning Pathway linking authentic climate-related challenges, STEM pedagogical processes, competency development, educational outcomes, and the potential development of informed climate action.

Conceptual Background

Integrated STEM Education as a Framework for Climate Change Learning

Integrated STEM education is generally distinguished from approaches in which Science, Technology, Engineering, and Mathematics are simply taught alongside one another. Its central educational proposition is that disciplinary knowledge can be connected through problems, practices, or design tasks that require students to draw on more than one disciplinary perspective. Thibaut et al. (2018), in Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education, identified problem-centred learning, inquiry, design, collaboration, and explicit integration of disciplines as recurring characteristics of integrated STEM instruction.

This distinction is particularly relevant to climate change because climate problems are inherently interdisciplinary. A question such as how a school could reduce its heat exposure cannot be adequately addressed by scientific knowledge alone. Students may need to investigate temperature patterns, collect and analyse data, understand heat transfer, calculate energy use, consider materials and building design, evaluate technological alternatives, and assess the feasibility of proposed interventions. Mathematics becomes a tool for analysing evidence, science provides explanatory models, technology provides measurement and information systems, and engineering provides a framework for designing and testing responses. (Thibaut et al., 2018; Portillo-Blanco et al., 2025)

The educational value of integration therefore lies not in the simultaneous presence of four subjects but in the functional relationship among disciplinary practices. Portillo-Blanco, Guisasola, and Zuza (2025), in Integrated STEM Education: Addressing Theoretical Ambiguities and Practical Applications, similarly emphasised the continuing need for conceptual clarity concerning what constitutes genuinely integrated STEM education. This issue is important when reviewing climate education because activities described as STEM may differ substantially in the degree to which disciplinary knowledge is actually integrated. Climate change can provide an authentic context for such integration. Students may investigate renewable energy systems, urban heat, carbon emissions, water scarcity, ecosystem change, food systems, climate adaptation, or energy efficiency. These problems can require the interpretation of scientific evidence as well as the development or evaluation of technological and engineering solutions. In this sense, climate change is not merely a topic that can be inserted into an existing STEM lesson. It can function as a problem context through which STEM practices become meaningful. (Portillo-Blanco et al., 2025; Thibaut et al., 2018)

2.2. Climate Literacy and Sustainability Competencies

Climate literacy is often associated with students' knowledge and understanding of climate systems, climate change causes, consequences, and possible responses. However, treating climate literacy as factual knowledge alone risks overlooking the capacities required to use knowledge in real-world contexts. The interdisciplinary competence framework developed for secondary students by the authors of Assessing Climate Literacy in Secondary Schools: Development and Validation of an Interdisciplinary Competence Test (2025) illustrates this broader perspective. The framework includes not only content knowledge but also knowledge generation and evaluation, information and communication, and the capacity to use evidence when considering climate-related issues.

This broader interpretation is consistent with the concept of sustainability competencies. Quintana-Cifuentes et al. (2019) examined sustainability competencies within secondary STEM education and showed that STEM learning can be connected to competencies extending beyond conventional disciplinary knowledge. Sposab and Rieckmann (2024) subsequently synthesised the development of sustainability competencies in secondary education and identified several recurring dimensions, including systems thinking, critical thinking, problem solving, collaboration, and engagement with complex sustainability issues. Climate change makes these competencies particularly important because students encounter uncertainty, conflicting interests, multiple scales of impact, and competing intervention options. For example, a proposed climate solution may reduce greenhouse gas emissions but involve economic costs or other environmental consequences. Students therefore need opportunities to compare alternatives, identify assumptions, interpret evidence, and consider trade-offs. (Martin et al., 2025; Sposab & Rieckmann, 2024)

Systems thinking is especially relevant. Climate change involves interconnected atmospheric, ecological, technological, economic, and social systems. Students who understand only isolated causal relationships may struggle to interpret feedback loops, delayed effects, cumulative impacts, or unintended consequences. STEM learning can make systems thinking more concrete through modelling, data analysis, simulation, engineering design, and analysis of real-world systems. The same principle applies to critical thinking and problem solving. Climate information is increasingly encountered through media, social networks, graphs, projections, and competing claims. Students need to distinguish evidence from assertion, evaluate the quality of information, recognise uncertainty, and justify conclusions. These practices overlap strongly with scientific and data literacy and can be embedded within STEM activities. (Sposab & Rieckmann, 2024; Quintana-Cifuentes et al., 2019)

From Knowledge Acquisition to Climate-Related Action

A central conceptual issue in climate change education is the relationship between knowledge and action. It is tempting to assume that if students understand climate change, they will automatically change their behaviour or participate in climate action. The evidence does not support such a simple causal assumption. The recent meta-analysis by Chen et al. (2026), The Effect of School Science Education on Students' Climate Literacy: A Three-Level Meta-Analysis, provides an important basis for this distinction. The analysis indicates stronger evidence for cognitive and attitudinal outcomes than for behavioural action. This distinction has implications for STEM education. A STEM project that asks students to calculate carbon emissions may successfully improve quantitative understanding. A project involving local temperature measurements may strengthen data literacy. An engineering design task may improve students' ability to generate and evaluate solutions. None of these outcomes, however, should automatically be interpreted as evidence that students will subsequently engage in sustained climate action.

The more defensible interpretation is that STEM learning can provide conditions that support action competence. These conditions may include understanding the problem, evaluating evidence, identifying possible responses, comparing alternatives, designing interventions, and recognising one's capacity to participate in decision making. Whether these capacities translate into actual behaviour depends on additional factors, including social context, perceived efficacy, opportunities for participation, institutional conditions, and students' emotional responses to climate change. (Chen et al., 2026; Sposab & Rieckmann, 2024)

This distinction also helps explain why authentic problems are important. When students investigate a climate-related issue in their own school or community, the problem becomes more immediate and potentially actionable. Place-based learning can reduce the psychological distance associated with a global phenomenon by connecting climate change with familiar environments, infrastructures, and community decisions. Recent work on place-based climate education and adaptation planning has similarly emphasised the importance of connecting climate learning with local contexts and adaptive capacity. The conceptual position adopted in this review is therefore that STEM education should not be expected to produce climate action directly. Instead, its potential contribution can be understood through a sequence in which students encounter an authentic climate challenge, engage in disciplinary and interdisciplinary inquiry, develop relevant competencies, evaluate possible responses, and acquire greater capacity for informed participation. (Hernandez et al., 2022; Hügel & Davies, 2024)

Narrative Review Method

This study adopted a narrative review approach to synthesize research on STEM education for climate change learning in secondary schools. The narrative design was selected because the relevant literature spans several interconnected fields, including climate change education, science education, integrated STEM education, sustainability education, socio-scientific issues, and educational technology. Rather than estimating a pooled effect size, the review sought to identify recurring pedagogical approaches, competencies, educational outcomes, and assessment practices across these research traditions. (Grant & Booth, 2009)

The review was guided by three research questions: (RQ1) Which STEM-based pedagogical approaches have been used to support climate change learning in secondary schools? (RQ2) Which climate-related, STEM, and sustainability competencies are developed through these approaches? and (RQ3) What educational outcomes and assessment approaches have been reported in the literature? These questions provided the main framework for organizing and interpreting the selected literature.

Relevant publications were identified from the literature available in major academic databases and scholarly search platforms, using combinations of keywords related to climate change education, climate literacy, STEM education, integrated STEM, secondary education, inquiry-based learning, project-based learning, problem-based learning, socio-scientific issues, STEAM, engineering design, place-based education, sustainability competencies, and climate change learning. Reference lists of relevant review articles and empirical studies were also examined to identify additional publications that were directly relevant to the research questions. (Grant & Booth, 2009)

The review primarily considered peer-reviewed international publications addressing students at the secondary-school level or studies whose educational context was directly transferable to secondary education. Particular attention was given to empirical studies that described a specific STEM-oriented pedagogical intervention or learning activity related to climate change and reported one or more educational outcomes. Review articles and conceptual studies were also considered when they provided relevant theoretical frameworks, definitions, or synthesis of evidence concerning climate change education, STEM education, or sustainability competencies.

Studies were considered relevant when they established a clear connection between climate change learning and at least one STEM-related dimension, such as scientific inquiry, quantitative analysis, technological application, engineering design, data interpretation, or interdisciplinary problem solving. Studies focusing exclusively on general environmental education without a meaningful STEM or climate change component were not treated as central evidence. Similarly, publications that addressed climate change only as a broad policy or environmental issue without an educational component were outside the main analytical scope.

The selected literature was organized using a thematic extraction framework. For each relevant study, information was recorded concerning author and year, country or educational context, education level, STEM approach, climate topic, pedagogical strategy, competencies addressed, educational outcomes, assessment methods, main findings, and reported limitations. This information was then compared across studies to identify recurring patterns and differences in how STEM approaches have been implemented and evaluated in climate change learning.

For the synthesis, the evidence was organized around the three research questions. The first level of analysis focused on the pedagogical approaches used to engage secondary students with climate-related problems. The second examined the competencies associated with these learning experiences, including climate literacy, scientific literacy, systems thinking, critical thinking, problem solving, data literacy, collaboration, decision making, and action competence. The third examined educational outcomes and assessment, distinguishing between cognitive outcomes, affective and motivational outcomes, competency development, and behavioural or action-oriented outcomes.

Because this is a narrative review, the synthesis does not claim to provide an exhaustive inventory of all publications on climate change and STEM education. Instead, it aims to provide an interpretive synthesis of representative and relevant evidence and to identify patterns, areas of convergence, and remaining gaps in the literature. Particular care was taken not to interpret the presence of a STEM activity alone as evidence of educational effectiveness. Where studies reported positive outcomes, the interpretation considered the pedagogical design, learning context, assessment approach, and type of outcome reported. This methodological approach provides the basis for the thematic synthesis presented in the following sections, where the evidence is examined according to STEM pedagogical approaches, competency development, and educational outcomes and assessment.

Results and Synthesis

RQ1: STEM-Based Pedagogical Approaches Used in Climate Change Learning

The literature does not indicate the dominance of a single STEM pedagogy for climate change learning in secondary schools. Instead, several approaches are used, often with considerable overlap in their instructional processes. Inquiry-based learning, problem- and project-based learning, socio-scientific issue approaches, engineering and design-based learning, place-based learning, and technology- and data-enhanced learning represent the most recurrent patterns. Their common feature is the movement away from climate change as a body of information toward climate change as a problem that students investigate, interpret, discuss, or address through evidence and proposed solutions.

Table 1. STEM Pedagogical Approaches Used in Climate Change Learning

Pedagogical approach	Representative studies	Typical climate context	Main learning function
Inquiry-based learning	Brumann et al. (2022)	Climate change and local environmental impacts	Investigation, evidence use, scientific reasoning
Problem-/project-based learning	Kundariati et al. (2025)	Climate mitigation and adaptation	Problem solving, planning, application
SSI–STEAM	Choi et al. (2021)	Climate change and socio-scientific issues	Socio-scientific reasoning, evaluation, action
Integrated STEM	Thibaut et al. (2018); Portillo-Blanco et al. (2025)	Authentic STEM problems	Disciplinary integration
Place-based learning	Hernandez et al. (2022)	Energy and local climate impacts	Contextual understanding and relevance
Technology- and data-enhanced learning	Kumar et al. (2023); Thacker et al. (2024)	Urban heat, climate datasets	Observation, data interpretation, motivation
Place-based adaptation and participatory approaches	Hügel and Davies (2024)	Local climate adaptation	Decision making and adaptive capacity

Source: Authors' synthesis based on the studies reviewed in this article.

Inquiry-Based Learning

Inquiry-based learning is particularly compatible with climate change education because climate phenomena involve relationships among multiple variables and cannot always be understood through direct observation alone. Instead of receiving predetermined explanations, students can formulate questions, collect or examine evidence, identify patterns, construct explanations, and revise their interpretations. (Brumann et al., 2022; Oliveira & Bonito, 2023)

Brumann, Ohl, and Schulz (2022), in Inquiry-Based Learning on Climate Change in Upper Secondary Education: A Design-Based Approach, provide a direct example of this orientation in upper secondary education. Their study positioned climate change as an object of inquiry and examined how students could engage with the issue through a structured learning design. The significance of this approach is not simply that students were exposed to climate content, but that they were required to work with evidence and develop explanations through an inquiry process.

This distinction is important when interpreting the contribution of STEM education to climate learning. An activity involving climate data does not automatically constitute inquiry-based STEM education. Inquiry becomes educationally meaningful when students must formulate or evaluate questions, interpret evidence, consider relationships among variables, and use their findings to justify conclusions. In this respect, inquiry can serve as the cognitive foundation for subsequent mathematical modelling, technological investigation, or engineering design.

The strength of inquiry-based learning is therefore closely related to the quality of the question and the degree of intellectual responsibility assigned to students. Highly structured inquiry may provide appropriate scaffolding for complex climate concepts, whereas more open inquiry may offer greater opportunities for student decision making but may also create additional cognitive demands. This suggests that the effectiveness of inquiry is likely to depend on the balance between learner autonomy, conceptual difficulty, available evidence, and teacher support.

Problem- and Project-Based Learning

Problem- and project-based learning provides another important pathway because climate change frequently presents problems without a single predetermined solution. Students may investigate how to reduce energy consumption, manage local heat exposure, reduce emissions, improve water use, or develop adaptation strategies. Kundariati et al. (2025), in Navigating Climate Change Education: A Problem-Oriented Project-Based Learning in Secondary Schools, illustrate this approach by organising learning around climate-related problems and project development. The study suggests that problem-oriented project work can create opportunities for students to connect climate concepts with practical responses and can strengthen engagement with the issue.

The distinctive contribution of project-based learning is the temporal and procedural structure it provides. Students generally need to define a problem, gather information, consider alternatives, develop a product or proposal, and communicate or evaluate the result. Consequently, the learning process can integrate scientific knowledge with planning, collaboration, communication, and decision making. However, the presence of a project alone should not be interpreted as evidence of integrated STEM learning. A project may remain largely descriptive or craft-oriented if students are not required to apply disciplinary concepts or generate evidence. For climate-focused STEM education, stronger integration occurs when the project requires students to use scientific explanations, quantitative analysis, technology, or engineering design to address an authentic problem.

Socio-Scientific Issues and STEAM

Climate change is also inherently a socio-scientific issue because decisions concerning mitigation and adaptation involve scientific evidence as well as economic, ethical, political, and social considerations. SSI-oriented approaches therefore provide a particularly useful connection between STEM knowledge and decision making. Choi et al. (2021), in The Impacts of a Climate Change SSI-STEAM Program on Junior High School Students' Climate Literacy, examined a climate change SSI-STEAM programme for junior high school students. The study is relevant because it moves climate learning beyond scientific explanation toward consideration of an issue in which evidence and possible responses must be evaluated.

The value of SSI-STEAM lies in its potential to connect disciplinary learning with argumentation and decision making. Students may be required to evaluate competing solutions, consider consequences, and justify a position rather than identify a single scientifically correct answer. This approach can consequently contribute to dimensions of climate literacy that are difficult to capture through conventional factual tests. Nevertheless, SSI-STEAM also presents an assessment challenge. A student's ability to express an informed opinion is not necessarily equivalent to demonstrating robust scientific reasoning or climate action competence. Assessment therefore needs to examine how students use evidence, recognise trade-offs, and justify decisions rather than simply whether they support a particular climate position.

Integrated STEM and Engineering Design

Integrated STEM provides a broader framework within which inquiry, problem solving, and engineering design can operate. Thibaut et al. (2018), in Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education, identified authentic problems, inquiry, design, collaboration, and disciplinary integration as recurring features of integrated STEM instruction at secondary level. Portillo-Blanco, Guisasola, and Zuza (2025), in Integrated STEM Education: Addressing Theoretical Ambiguities and Practical Applications, further emphasised the importance of conceptual clarity when distinguishing genuinely integrated STEM from activities in which several STEM subjects merely appear together. This distinction is particularly important for climate change education.

For example, students investigating school energy consumption may collect temperature and electricity data, analyse energy-use patterns mathematically, examine scientific principles of heat transfer, use digital measurement technologies, and design interventions to improve energy efficiency. Such an activity creates functional relationships among STEM disciplines because each contributes to understanding or solving the same problem. Engineering design adds another dimension by introducing criteria, constraints, alternative solutions, testing, and iteration. Climate problems rarely have perfect solutions. A proposed intervention may reduce emissions but increase cost, require additional materials, or produce other environmental consequences. Engineering design therefore provides a useful structure for teaching students to reason about trade-offs rather than search for a single predetermined answer.

Place-Based Learning

Place-based learning connects climate education with the physical and social environments in which students live. This approach is particularly relevant because climate change can otherwise remain psychologically distant, especially when students encounter it primarily through global statistics and projections. Hernandez et al. (2022), in Place-Based Education in High School Science: Situating Energy and Climate Change in Students' Communities, illustrate how local energy and climate contexts can be incorporated into secondary science learning. Such approaches can make climate processes more observable and relevant by connecting abstract concepts with local infrastructure, environmental conditions, and community experiences.

The contribution of place-based learning is not limited to increasing relevance. Local contexts can also provide authentic data and decision-making problems. Students may measure temperature differences within their school, investigate energy consumption, examine vegetation and heat exposure, or consider local adaptation options. These activities can subsequently become entry points for inquiry, mathematical analysis, and engineering design. Hügel and Davies (2024), in Expanding Adaptive Capacity: Innovations in Education for Place-Based Climate Change Adaptation Planning, further highlight the relationship between education and place-based adaptation planning. Their work suggests that climate education can extend toward participatory consideration of local adaptation rather than remaining confined to classroom knowledge acquisition.

Technology- and Data-Enhanced Learning

Climate change is a data-rich field, making technology and data analysis particularly relevant to STEM learning. Temperature records, precipitation measurements, greenhouse gas emissions, energy consumption, sea-level changes, and other environmental indicators provide opportunities for students to work with authentic quantitative information. Kumar et al. (2023), in Using Empirical Science Education in Schools to Improve Climate Change Literacy, examined empirical science learning activities designed to improve climate change literacy. The study illustrates how direct investigation and empirical evidence can strengthen students' connection between scientific concepts and observable environmental phenomena.

Thacker et al. (2024), in Supporting Secondary Students' Climate Change Learning and Motivation Using Novel Data and Data Visualizations, examined the use of climate data and data visualisations to support secondary students' learning and motivation. This work is particularly relevant to STEM because it illustrates the potential of data representation to connect climate science with quantitative reasoning and students' interpretation of evidence. The pedagogical value of data-based learning, however, depends on more than providing students with graphs. Meaningful data literacy requires students to identify variables, interpret trends, recognise uncertainty, compare evidence, question data sources, and use quantitative information to support conclusions. Consequently, data visualisation should be considered a component of evidence-based reasoning rather than an end in itself.

RQ2: Climate-Related, STEM, and Sustainability Competencies

The second research question concerns what students are expected to develop through STEM-oriented climate learning. Across the reviewed literature, competencies extend beyond climate knowledge and include scientific reasoning, systems thinking, critical thinking, problem solving, data literacy, design competence, collaboration, decision making, and action competence.

The distribution of these competencies varies according to pedagogy. Inquiry-based learning places greater emphasis on investigation and evidence-based reasoning. Data-oriented activities foreground quantitative interpretation. Engineering design emphasises problem solving, design reasoning, and evaluation of alternatives. SSI approaches more explicitly address argumentation and decision making. Place-based approaches may strengthen contextual understanding and perceptions of relevance.

Table 2. Climate-Related and STEM/Sustainability Competencies Developed Through STEM-Based Climate Learning

Competency	Application in climate-STEM learning	Typical learning processes
Climate/scientific literacy	Understanding causes, mechanisms, impacts, and responses	Conceptual learning, investigation
Systems thinking	Understanding relationships and feedbacks among climate, environmental, and human systems	Modelling, systems analysis
Critical thinking	Evaluating claims and evidence	Inquiry, argumentation
Problem solving	Identifying and addressing authentic climate problems	PBL, engineering design
Data literacy	Interpreting measurements, graphs, models, and trends	Data analysis, visualisation
Design competence	Developing, testing, and improving solutions	Engineering design
Collaboration	Working collectively on complex problems	Projects, inquiry, SSI
Decision making	Comparing alternatives and considering trade-offs	SSI, design, adaptation planning
Action competence	Developing capacity to participate in informed climate-related action	Projects, decision tasks, reflection

Source: Authors' synthesis based on the studies reviewed in this article.

Climate and Scientific Literacy

Climate knowledge remains the most visible component of climate learning. Students need to understand fundamental concepts, causal mechanisms, impacts, and possible responses before they can critically evaluate climate-related claims or solutions. However, recent research supports a broader conceptualisation. Aeschbach, Schwichow, and Rieß (2025), in Effectiveness of Climate Change Education—A Meta-Analysis, examined climate change education outcomes across knowledge, attitudes, and behaviour. Their synthesis reinforces the importance of distinguishing among these outcome dimensions rather than treating climate education as synonymous with knowledge acquisition.

Chen, Ren, and Yang (2026), in The Effect of School Science Education on Students' Climate Literacy: A Three-Level Meta-Analysis, likewise examined climate cognition, attitudes, and action as related but distinct dimensions. Their findings provide further support for interpreting climate literacy as a multidimensional educational outcome rather than a simple factual construct. For STEM education, this means that climate literacy should encompass not only knowing what climate change is, but also understanding how evidence is generated, interpreted, communicated, and applied in decision making.

Systems Thinking

Systems thinking is particularly important because climate change emerges from interactions among multiple interconnected systems. Students need to recognise that changes in one component can influence other components through direct and indirect relationships. Sposab and Rieckmann (2024), in Development of Sustainability Competencies in Secondary School Education: A Scoping Literature Review, identify systems thinking as one of the recurring competencies in sustainability education. Earlier, Quintana-Cifuentes et al. (2019), in Sustainability Competencies in STEM Education at Secondary Schools: A Systematized Literature Review, also identified systems-oriented competencies as important within secondary STEM education. STEM learning can provide concrete mechanisms for developing systems thinking. Students can construct models, analyse datasets, investigate energy flows, examine feedback mechanisms, or simulate possible interventions. The important point is that these activities should require students to consider relationships among components rather than analyse isolated variables.

Critical Thinking and Evidence-Based Reasoning

Climate change is accompanied by uncertainty, competing claims, incomplete information, and differences in interpretations of potential responses. Students therefore need to distinguish between claims, evidence, and reasoning. Inquiry-based STEM learning can support this competency by requiring students to construct conclusions from observations or datasets. SSI approaches can extend the process by asking students to compare arguments and justify decisions. Data-oriented activities can further require students to examine whether a particular interpretation is supported by quantitative evidence.

This competency is particularly important in contemporary information environments where students encounter climate information through multiple sources. The educational goal should not be to make students accept a predetermined position, but to enable them to evaluate the credibility and relevance of evidence and to justify conclusions appropriately.

Problem Solving and Design Competence

Climate change problems frequently involve multiple constraints and competing criteria. Students may therefore need to determine not only whether a solution is scientifically plausible but also whether it is technically feasible, economically reasonable, environmentally responsible, and socially acceptable. Engineering design provides a particularly appropriate structure for this type of reasoning. Students can define a problem, establish criteria, generate alternative solutions, construct or model a response, test it, analyse weaknesses, and revise the design.

Portillo-Blanco et al. (2025) emphasise the importance of real-world problems and disciplinary integration in integrated STEM. When applied to climate learning, this perspective suggests that design tasks should be connected to genuine climate-related challenges and should require explicit use of disciplinary knowledge.

Data Literacy

Data literacy is increasingly important in climate education because students encounter climate information in numerical and visual forms. Temperature trends, emissions data, energy-use records, precipitation patterns, and projections all require interpretation. Thacker et al. (2024) demonstrate the relevance of data and data visualisation for supporting secondary students' climate learning and motivation. However, climate data literacy requires more than the ability to read a graph. Students should be able to identify variables, recognise trends, interpret scales, consider uncertainty, compare datasets, and evaluate whether a conclusion is justified by the available evidence. This makes data literacy an important point of convergence between climate education and mathematics-oriented STEM learning.

Action Competence

Action competence represents the most difficult competency to establish empirically. It involves more than expressing concern about climate change or reporting an intention to behave differently. It concerns the capacity to understand a problem, evaluate alternatives, participate in decision making, and identify feasible ways of responding. Sposab and Rieckmann (2024) position action competence within the broader framework of sustainability competencies. Choi et al. (2021) also provide evidence that a climate change SSI-STEAM programme can address the action dimension of climate literacy. Nevertheless, action competence should not be equated with demonstrated long-term behavioural change. Chen et al. (2026) found stronger evidence for cognitive and attitudinal dimensions than for an overall behavioural effect of school science education on climate action. Therefore, a student's improved intention to act should not be presented as equivalent to sustained behavioural change.

RQ3: Educational Outcomes and Assessment Approaches

The third research question examines what outcomes have been reported and how they have been assessed. The literature demonstrates considerable variation in both outcome definitions and assessment instruments.

Table 3. Educational Outcomes and Assessment Approaches

Outcome domain	**Typical indicators**	**Common assessment approaches**
Climate knowledge	Causes, processes, impacts, responses	Pre/post tests, concept tests
Climate literacy	Knowledge, information evaluation, perceptions, action dimensions	Climate literacy instruments
Scientific reasoning	Evidence interpretation and explanation	Performance tasks, inquiry reports
Systems thinking	Relationships, interactions, feedbacks	Concept maps, models, scenario tasks

Outcome domain	**Typical indicators**	**Common assessment approaches**
Problem solving	Problem identification and solution development	Authentic tasks, project products
Design competence	Criteria, prototype quality, testing and iteration	Design rubrics, portfolios
Data literacy	Graph, dataset, and quantitative interpretation	Data-analysis tasks
Motivation/interest	Engagement, interest, self-efficacy	Questionnaires, interviews
Attitudes	Concern, perceptions, values	Questionnaires, interviews
Action competence	Agency, decision making, intentions	Scenario tasks, self-report, artefacts
Behaviour	Reported or observed climate-related actions	Observation, longitudinal follow-up

Source: Authors' synthesis based on the studies reviewed in this article.

Knowledge and Conceptual Understanding

Knowledge and conceptual understanding are the most consistently assessed outcomes in climate change education. This is partly because knowledge can be measured relatively efficiently through pre/post tests and standardised instruments. Aeschbach et al. (2025) provide particularly relevant quantitative evidence. Their meta-analysis, Effectiveness of Climate Change Education—A Meta-Analysis, found a medium-to-large overall effect of climate change education on knowledge. This provides relatively strong support for the proposition that educational interventions can improve students' understanding of climate change.

Chen et al. (2026) similarly found positive effects associated with school science education and climate literacy. Together, these findings suggest that cognitive gains represent the most established contribution of school-based climate education. However, improved knowledge should not be interpreted as sufficient evidence of successful climate education. A student may understand the causes and consequences of climate change without being able to evaluate competing mitigation strategies, interpret local data, or participate in climate-related decision making.

Motivation, Interest, and Attitudes

Several STEM-oriented approaches also report changes in students' motivation, engagement, or attitudes. These outcomes are particularly relevant when learning involves authentic problems or data connected to students' own environments. Thacker et al. (2024) examined the use of climate data and data visualisations partly in relation to students' motivation. Their study demonstrates that data-oriented learning can connect abstract climate processes with interpretable evidence and potentially strengthen students' engagement. Place-based and project-oriented learning may similarly increase perceived relevance because students can see how climate change relates to their own communities. However, positive engagement should be distinguished from learning achievement. Students may enjoy an activity without necessarily developing deeper conceptual understanding, and increased concern does not automatically indicate greater action competence.

Scientific Reasoning and Data Interpretation

STEM-oriented climate education has particular potential to develop reasoning processes that conventional content-based instruction may not directly assess. Inquiry tasks can require students to formulate explanations from evidence. Data-based learning can require interpretation of trends and uncertainty. Engineering activities can require students to evaluate whether test results support a design decision.

These outcomes are often assessed through student reports, performance tasks, project products, or teacher observation rather than conventional knowledge tests. This creates a methodological issue for cross-study synthesis because different instruments may measure similar competencies under different labels. The distinction between what students know and what students can do with what they know is therefore important. A climate knowledge test may demonstrate conceptual learning but provide little information about a student's capacity to interpret evidence or design a response.

Systems Thinking and Decision Making

Systems thinking and decision making are more difficult to assess than factual knowledge. Concept maps, causal models, scenario-based tasks, and structured decision activities can provide richer evidence because they require students to represent relationships and consider consequences. SSI and adaptation-oriented approaches are especially relevant here because students may need to evaluate multiple alternatives rather than identify one correct answer. Hügel and Davies (2024) demonstrate how education can be connected with place-based climate adaptation planning, creating opportunities for students to consider local climate risks and possible responses. Nevertheless, assessment remains inconsistent across studies. There is a need for greater use of validated instruments and performance-based assessment capable of capturing the complexity of systems thinking and decision making.

Action-Related Outcomes and Behavioural Change

The distinction between action intention and actual behaviour is particularly important. Many educational studies rely on self-reported intentions or attitudes because actual behaviour is difficult to measure within the timeframe of a school intervention. The available evidence therefore supports a cautious interpretation. Climate education can improve students' knowledge and may influence attitudes, motivation, perceptions of relevance, and intentions. However, evidence of sustained behavioural change is less consistent.

Chen et al. (2026) provide an important recent quantitative basis for this conclusion by distinguishing cognitive, attitudinal, and action dimensions in their meta-analysis. The absence of a clear overall behavioural effect means that climate STEM education should not claim to have changed students' long-term behaviour unless such behaviour has actually been measured. This distinction is central to the present review. Action competence should be treated as a learning capacity, whereas climate behaviour is an outcome that requires separate empirical evidence.

Cross-Study Synthesis

Taken together, the reviewed literature suggests that STEM-oriented climate education is most educationally meaningful when several components are aligned. First, students need an authentic climate-related problem or question. This can be a global problem translated into a local context, such as school energy consumption, urban heat, water management, or adaptation to local environmental risks. Second, the problem should require evidence-based investigation. Students should collect, analyse, or critically evaluate evidence rather than simply receive information. Third, disciplinary knowledge should be functionally integrated. Science should explain phenomena, mathematics should support measurement or modelling, technology should support investigation or implementation, and engineering should provide processes for designing and testing solutions where appropriate. Fourth, students should be given opportunities to evaluate alternatives and make justified decisions. This is particularly important because climate problems rarely have a single optimal solution. Fifth, assessment should correspond to the competencies that the learning activity is designed to develop. If an activity aims to develop systems thinking, assessing only factual recall produces an incomplete picture of learning. Similarly, if an engineering project aims to develop design competence, the assessment should examine criteria, constraints, testing, iteration, and reasoning.

Discussion

From Climate Content to Climate Problem-Solving

The synthesis indicates that the educational contribution of STEM to climate change learning is best understood not simply in terms of adding climate-related content to STEM curricula, but in terms of changing how students engage with climate problems. (Thibaut et al., 2018; Portillo-Blanco et al., 2025)

Across the reviewed studies, the most meaningful learning designs tend to position students as investigators, analysts, designers, or decision makers rather than passive recipients of information. Inquiry-based learning enables students to investigate evidence and construct explanations, while project- and problem-based learning gives students opportunities to apply knowledge to authentic situations. Engineering design extends this process by requiring students to generate, test, and revise potential solutions. Socio-scientific approaches add another dimension by requiring students to evaluate competing perspectives and make evidence-informed decisions. (Brumann et al., 2022; Kundariati et al., 2025; Choi et al., 2021)

This pattern is consistent with the broader literature on integrated STEM education. Thibaut et al. (2018), in *Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education*, identified authentic problem contexts, inquiry, design, collaboration, and disciplinary integration as important characteristics of integrated STEM instruction. The relevance of these characteristics becomes particularly apparent in climate education because climate problems themselves are characterised by complexity, uncertainty, multiple stakeholders, and competing solutions.

The findings therefore suggest that climate change provides a particularly suitable context for integrated STEM when the learning activity is structured around an authentic problem requiring students to mobilise knowledge from several disciplines. A lesson that merely introduces climate change terminology in a science class may contribute to climate knowledge, but it does not necessarily exploit the distinctive educational potential of STEM.

The distinction is important because the term "STEM" is sometimes applied broadly to activities involving technology or practical work without demonstrating meaningful integration among disciplines. Portillo-Blanco et al. (2025), in *Integrated STEM Education: Addressing Theoretical Ambiguities and Practical Applications*, highlight precisely this conceptual challenge. The present review consequently suggests that future climate-STEM research should report more explicitly how scientific, mathematical, technological, and engineering knowledge are functionally connected within an intervention.

Why Inquiry and Authentic Problems Matter

One of the strongest patterns across the literature is the importance of authentic inquiry and problem contexts. Climate change is difficult to teach effectively when it remains geographically and psychologically distant from students. Global temperature trends, atmospheric carbon dioxide concentrations, sea-level projections, and international mitigation targets are scientifically important, but they can be difficult for students to connect with their own experiences. (Brumann et al., 2022; Kumar et al., 2023; Thacker, 2024)

Place-based and inquiry-oriented STEM approaches can reduce this distance by transforming global climate issues into questions that can be investigated locally. Students can examine the thermal characteristics of their school, measure local temperature variation, investigate energy consumption, analyse rainfall or water-use data, or consider how local infrastructure could be adapted to climate risks. (Hernandez et al., 2022; Brumann et al., 2022)

Kumar et al. (2023), in *Using Empirical Science Education in Schools to Improve Climate Change Literacy*, demonstrate the potential of empirical investigation to connect climate science with students' observations and measurements. Similarly, research involving climate data and visualisation has shown the potential of data-rich learning environments to support secondary students' climate learning and motivation. The educational value of such activities derives from the relationship between experience and explanation. Students first encounter a phenomenon or problem, then use scientific concepts and quantitative evidence to explain it. This sequence can make abstract climate concepts more meaningful while simultaneously developing scientific reasoning.

However, authenticity should not be interpreted as simply taking students outside the classroom. A local activity becomes educationally powerful when students must use evidence to answer a meaningful question or make a justified decision. Consequently, future studies should distinguish between contextual authenticity and cognitive authenticity. The former concerns whether the problem is situated in a real environment; the latter concerns whether students are actually required to reason in ways similar to scientists, engineers, or decision makers.

STEM Competencies and Climate Literacy Are Complementary

The synthesis also indicates that climate literacy and STEM competencies should not be treated as competing educational goals. Climate literacy provides students with knowledge and understanding of climate systems and climate-related issues. STEM competencies provide tools for investigating, analysing, modelling, designing, and evaluating those issues. (Martin et al., 2025; Sposab & Rieckmann, 2024)

For example, climate literacy may enable a student to explain why urban areas can experience elevated temperatures, while data literacy enables the student to analyse temperature measurements. Systems thinking enables the student to consider relationships among vegetation, surface materials, building density, energy use, and human health. Engineering design can then be used to develop and evaluate possible interventions. This relationship suggests that climate-STEM education is potentially strongest when knowledge and practice are integrated.

Quintana-Cifuentes et al. (2019), in *Sustainability Competencies in STEM Education at Secondary Schools: A Systematized Literature Review*, highlighted the potential of STEM education to contribute to sustainability competencies. Sposab and Rieckmann (2024), in *Development of Sustainability Competencies in Secondary School Education: A Scoping Literature Review*, similarly emphasised competencies such as systems thinking, critical thinking, problem solving, collaboration, and decision making. The present review extends this perspective specifically to climate change learning by suggesting that these competencies can function as mechanisms connecting climate knowledge to informed participation. In other words, students need both knowledge about climate change and capacity to work with that knowledge.

The Evidence for Learning Outcomes Is Stronger for Cognition Than Action

One of the clearest findings emerging from recent evidence is the difference between cognitive and action-related outcomes. Aeschbach et al. (2025), in *Effectiveness of Climate Change Education—A Meta-Analysis*, synthesised 53 eligible studies and found significant effects for knowledge-related outcomes, attitude-related outcomes, and behaviour-related outcomes. Their pooled effects were approximately 0.77 for knowledge, 0.39 for attitudes, and 0.36 for behaviour. However, the authors also reported substantial heterogeneity and called for higher-quality research. Chen et al. (2026), in *The Effect of School Science Education on Students' Climate Literacy: A*

Three-Level Meta-Analysis, provide an even more recent synthesis based on 33 experimental and quasi-experimental studies involving 8,044 students. Their overall effect for climate literacy was large (g = 1.01), while the effects for cognition and attitude were also statistically significant. In contrast, the action dimension was based on only three effect sizes and did not reach statistical significance (g = 0.34, 95% CI −0.63 to 1.32). These findings should not be interpreted as contradictory. Rather, they demonstrate that educational outcomes depend strongly on how climate learning and action are conceptualised and measured. Knowledge is relatively proximal to classroom instruction. Students can acquire information, construct conceptual understanding, and demonstrate this understanding in a relatively short intervention. Attitudes may require more sustained engagement but can still be influenced through meaningful learning experiences.

Behaviour is different. Actual climate-related behaviour is influenced by factors outside the classroom, including family practices, infrastructure, economic conditions, social norms, perceived efficacy, and opportunities for action. Consequently, a short-term school intervention may improve students' knowledge or intentions without producing measurable changes in long-term behaviour. The distinction has an important implication for STEM education research. Studies should avoid presenting improved climate knowledge, attitudes, or behavioural intentions as direct evidence of climate action. Instead, the results should specify whether the intervention affected knowledge, competency, intention, reported behaviour, observed behaviour, or sustained behaviour. (Aeschbach et al., 2025; Chen et al., 2026)

Limitations of the Review

This review has several limitations. First, it adopts a narrative rather than systematic-review or meta-analytic methodology. The synthesis therefore seeks to identify conceptual and empirical patterns rather than provide an exhaustive estimate of intervention effects. Second, terminology across the literature is inconsistent. Studies may describe similar pedagogical practices using different labels, while the same label may refer to substantially different instructional designs. Third, the evidence base varies considerably in study design, educational level, intervention duration, assessment methods, and outcome definitions. Direct comparisons between individual interventions should therefore be made cautiously. Fourth, the evidence concerning behavioural and action-related outcomes remains comparatively limited. The review consequently avoids making strong causal claims concerning the ability of STEM education to produce sustained climate behaviour. Finally, the review focuses primarily on secondary education. Findings from primary education, higher education, informal education, or adult education may provide useful theoretical insights but should not automatically be generalised to secondary-school contexts.

Conclusion

Climate change presents a distinctive challenge for secondary education because it requires students to understand complex scientific processes while also considering technological possibilities, quantitative evidence, engineering solutions, social consequences, and decisions under uncertainty. The literature reviewed in this study indicates that STEM education can provide a useful framework for addressing this complexity when climate change is approached through authentic problems, inquiry, data analysis, interdisciplinary learning, engineering design, and evidence-based decision making.

Among the pedagogical approaches identified, inquiry-based learning, problem- and project-based learning, socio-scientific issue approaches, engineering design, place-based learning, and technology- and data-enhanced learning provide complementary pathways for climate change learning. The competency evidence suggests that the potential contribution of STEM extends beyond climate knowledge to systems thinking, critical thinking, data literacy, problem solving, design competence, collaboration, decision making, and action competence.

The strongest evidence currently concerns cognitive learning outcomes. Recent meta-analytic evidence demonstrates substantial positive effects of climate change education and school science education on climate-related knowledge and cognition, with additional evidence for attitudinal outcomes. However, evidence concerning climate action remains more limited and should be interpreted cautiously. The central implication is therefore that STEM education should not be presented as a direct mechanism for producing climate action. Its more defensible contribution is to create learning conditions in which students can understand climate processes, investigate evidence, analyse data, evaluate alternatives, design possible responses, and develop the competencies required for informed participation.

Future climate-STEM research should consequently move beyond measuring whether students "know more" about climate change. Greater attention should be given to what students can investigate, model, evaluate, design, justify, and do with their knowledge. In this sense, the educational value of STEM for climate change learning lies not simply in integrating four disciplines, but in using their combined practices to help students move from understanding climate problems toward evidence-informed problem solving and meaningful participation.

Suggestions and Recommendations

Future studies should use longitudinal designs to determine whether climate-related competencies and learning gains are sustained after STEM interventions end (Aeschbach et al., 2025; Chen et al., 2026).

Assessment should be aligned explicitly with the intended competency, combining knowledge measures with validated assessments of systems thinking, data literacy, design reasoning, decision making, and action competence (Martin et al., 2025; Sposab & Rieckmann, 2024).

Researchers should distinguish climate-action intentions and self-reported behaviour from observed or sustained behaviour and should report these outcomes separately (Aeschbach et al., 2025; Chen et al., 2026).

Comparative studies across inquiry-based, project/problem-based, SSI-STEAM, engineering-design, place-based, and data-enhanced approaches would help identify which pedagogies are most effective for particular competencies and outcomes (Thibaut et al., 2018; Tijani & Adeduyigbe, 2026).

Greater geographical and cultural diversity is needed so that climate-STEM learning is not evaluated primarily through a small number of educational contexts and can better address locally specific climate risks (Hernandez et al., 2022; Sposab & Rieckmann, 2024).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The author was solely responsible for the conceptualization, literature search and selection, data synthesis, analysis and interpretation, manuscript preparation, revision, and final approval of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The author was solely responsible for the conceptualization, literature search and selection, data synthesis, analysis and interpretation, manuscript preparation, revision, and final approval of the manuscript.