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Teaching Climate Change as a Socio-Scientific Issue: A Systematic Review of Strategies and Outcomes in Secondary Science Education (2021-2026)

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Abstract

This systematic review examines the empirical literature on teaching climate change as a socio-scientific issue (SSI) in secondary science education between 2021 and 2026. Following PRISMA guidelines, 43 peer-reviewed articles were analyzed to identify key instructional strategies, student learning outcomes, and implementation challenges. Findings reveal four primary instructional approaches: argumentation and debate, project-based learning, technology-enhanced modeling, and place-based/action-oriented pedagogies. Student outcomes include enhanced conceptual understanding, improved argumentation and critical thinking skills, shifts in environmental attitudes, and increased action competence. However, significant implementation challenges persist, including teacher efficacy barriers, curriculum constraints, and the need to balance scientific complexity with emotional engagement. The review highlights the importance of teacher professional development and culturally responsive approaches to SSI-based climate education. Future research directions include longitudinal studies on behavioral outcomes, comparative effectiveness research, and exploration of SSI integration in diverse cultural contexts.

Subject Areas

Science Education, Environmental Education, Educational Research

Keywords

Socio-Scientific Issues, Climate Change Education, Secondary Science, Systematic Review, Instructional Strategies, Student Outcomes

1. Introduction

Global climate change represents one of the most significant challenges of the twenty-first century, characterized by scientific complexity, social controversy, and profound ethical implications. As a quintessential socio-scientific issue (SSI), climate change demands that citizens navigate not only scientific concepts but also cultural, economic, political, and moral considerations. The interdisciplinary nature of climate change makes it an ideal focus for SSI instruction, which positions complex societal issues at the center of science teaching to promote functional scientific literacy.

Science educators have increasingly identified climate change as a critical component of what some scholars term the "triple planetary crisis," encompassing climate change, biodiversity loss, and pollution. Recent scholarship has located the origins of these ecological crises in systems of racial capitalism and extractivist colonialism, arguing that teaching about environmental crises must account for these historical and structural dimensions. This recognition has prompted calls for a paradigm shift in climate change and sustainability education (CCSE) to focus on root causes and justice implications [1].

The urgency of climate education is underscored by international policy frameworks. UNESCO's 2030 Agenda for Sustainable Development identifies the need to "ensure the provision of learning opportuniti es so that all youth and adults acquire functional scientific literacy" to foster active citizenship [2]. Secondary science classrooms represent a crucial site for this education, as adolescents are at a developmental stage where they can engage with complex reasoning about scientific and social issues while forming lasting environmental attitudes and behaviors.

Despite growing consensus on the importance of SSI-based climate education, significant questions remain about effective implementation. Teachers face numerous challenges, including the controversial nature of climate change, the difficulty of representing long-term and large-scale phenomena, and the need to balance scientific accuracy with emotional engagement. Additionally, research has shown that science classes are less likely than other educational contexts to address issues of justice in climate education, constrained by policies, standards, and teachers' beliefs that divorce scientific phenomena from their socio-political contexts.

The past five years have witnessed substantial growth in empirical research on SSI-based climate education. However, this literature remains fragmented across disciplines, educational levels, and methodological approaches. A systematic synthesis is needed to consolidate what we know about effective strategies, student outcomes, and persistent challenges.

Research Questions

This systematic review addresses the following research questions:

1) What instructional strategies have been employed in teaching climate change

as a socio-scientific issue in secondary science education?

2) What student outcomes are associated with SSI-based climate change instruction?

3) What challenges and barriers do teachers face in implementing SSI-based climate education?

4) What gaps exist in the current literature, and what directions for future research can be identified?

2. Literature Review

2.1. Theoretical Foundations of SSI Pedagogy

The socio-scientific issues (SSI) framework emerged from recognition that science education must prepare students to navigate the complex intersections of science and society. Unlike traditional approaches that privilege scientific reasoning in isolation, SSI instruction attends to normative factors, personal values, and social contexts that are frequently overlooked. The framework draws on developmental psychology, sociology, and philosophy to examine how instructional resources can facilitate learning about science content embedded in socially relevant situations while supporting epistemological growth and character development [3].

Well-designed SSI instruction relies on several key principles. First, instruction centers on an issue that is complex, contentious, and connected to science—climate change exemplifies these characteristics. Second, learners are given scaffolded opportunities to analyze information from various sources while developing skills necessary to resolve the issue. Third, a culminating experience allows learners to synthesize information and propose solutions. The SSI framework positions students to weigh scientific information alongside cultural, economic, political, and moral/ethical considerations, developing the capacity for perspective-taking and empathetic concern.

Recent theoretical developments have integrated SSI with other pedagogical approaches. The SSI-based STEAM framework merges SSI perspectives with arts-integrated practices, emphasizing interdisciplinary thinking, affective learning, and authentic contexts. This approach is organized around four key principles: enacted values and practices, affective learning, authentic context and activities, and interdisciplinary thinking and integrated practices, implemented through a 6E inquiry instructional model (engage, explore, explain, elaborate, evaluate, enact) [4].

2.2. Climate Change as a Socio-Scientific Issue

Climate change possesses distinctive characteristics that make it particularly suitable for SSI pedagogy. Its global scope and long-term timescale create challenges for comprehension, as effects occur incrementally on scales that are difficult for students to fully appreciate. The issue is frequently accompanied by heated arguments regarding its origin and human capacity to intervene, making it geopolitically contentious. People's beliefs about the causes of climate change influence

both their risk perceptions and mitigating behaviors, underscoring the importance of accurate understanding.

Importantly, climate change education increasingly emphasizes justice dimensions. Climate justice connects to human rights, including the right to live in a safe, clean, healthy, and sustainable environment. Indigenous visions of climate justice emphasize the rights of more-than-human species and communities, expanding the ethical frame beyond anthropocentric concerns. Scholars argue that any thorough explanation of climate and environmental justice must connect systems of racial capitalism and colonialism with extractive industry and scientific enterprise.

The complexity of climate change as an SSI creates several pedagogical tensions. While research emphasizes student-centered curricula, teachers remain central in driving lessons toward justice orientations. Traditional CCSE often emphasizes individual responsibility, while justice orientations push toward collective action. Teachers must balance local environmental justice concerns with global understanding of the triple planetary crisis, recognizing the extractive relationship between Global North and South as a key driver of environmental degradation.

2.3. Previous Reviews and Research Gaps

A systematic review covering 1997-2021 found that SSI instruction in environmental and sustainability contexts most frequently employs argumentation, role-play, case-based inquiry, and project-based learning. Research has demonstrated that SSI approaches enhance students' argumentation skills, enabling them to analyze complex environmental issues from multiple perspectives [3].

However, existing reviews have not specifically focused on climate change as an SSI in secondary education, nor have they systematically examined the most recent five years of scholarship, a period marked by increased attention to climate justice, technological integration, and cross-cultural perspectives. The present review addresses this gap.

3. Methodology

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

3.1. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

- Population: Focused on secondary education (grades 6 - 12, approximately ages 11 - 18)
- Intervention: Implemented SSI-based instruction related to climate change or closely related environmental issues. Studies addressing broader environmental topics (e.g., general sustainability, antibiotic resistance, or disposable plastics without explicit connection to climate change) were excluded to maintain focus on climate change as the core SSI. During screening, this criterion was

applied by examining whether the study's stated research focus, intervention description, or central SSI context explicitly mentioned climate change or its direct consequences. Studies that used climate change as one of several contexts were included only if climate change received substantial emphasis in the intervention or analysis.

- Outcomes: Reported empirical data on student learning outcomes, teacher practices, or implementation factors
- Design: Original empirical research (qualitative, quantitative, or mixed methods)
- Language: Published in English
- Timeframe: 2021-2026

Studies were excluded if they:

- Focused solely on higher education or primary education without secondary components
- Addressed environmental education without explicit SSI framing
- Were theoretical or position papers without empirical data
- Were conference proceedings, book chapters, or dissertations (to ensure peer review quality)

3.2. Search Strategy and Databases

A comprehensive literature search was conducted on March 15, 2026 in the following databases. Database-specific search strings were employed to accommodate varying syntax requirements:

Web of Science Core Collection:

TS = ("socio-scientific issues" OR "SSI" OR "socioscientific issues") AND TS = ("climate change" OR "global warming" OR "climate crisis") AND TS = ("science education" OR "science teaching" OR "secondary education" OR "high school" OR "secondary school") Refined by: Document Types: Article; Publication Years: 2021-2026; Web of Science Categories: Education Educational Research OR Education Scientific Disciplines.

ERIC (via EBSCOhost):

(DE "Science Education" OR DE "Secondary School Science") AND (DE "Climate" OR "climate change" OR "global warming") AND (DE "Socio-scientific Issues" OR "SSI" OR "socioscientific issues") Search mode: Boolean/Phrase; Publication Year: 2021-2026; Peer reviewed only.

Scopus:

TITLE-ABS-KEY ("socio-scientific issues" OR "SSI" OR "socioscientific issues") AND TITLE-ABS-KEY ("climate change" OR "global warming" OR "climate crisis") AND TITLE-ABS-KEY ("science education" OR "science teaching" OR "secondary education" OR "high school") Limit to: Article; Publication Year: 2021-2026; Subject Area: Social Sciences.

Education Source (via EBSCOhost):

(DE "Science Education" OR DE "Secondary Education") AND (DE "Climate

Change" OR "global warming") AND (DE "Socio-scientific Issues" OR "SSI") Search mode: Boolean/Phrase; Publication Year: 2021-2026; Peer reviewed only.

3.3. Screening and Selection Process

The initial search yielded 847 records. After removing duplicates (n = 312), 535 records underwent title and abstract screening. Two reviewers independently screened records against inclusion criteria, with disagreements resolved through discussion. Inter-rater agreement for title/abstract screening was substantial (Cohen's $\kappa = 0.81$, 92% agreement). This process eliminated 432 records. The remaining 103 full-text articles were assessed for eligibility, resulting in the exclusion of 60 articles primarily due to: insufficient focus on SSI framework (n = 28), lack of empirical data (n = 17), incorrect age level (n = 11), or non-English language (n = 4). Full-text screening agreement was also strong (Cohen's $\kappa = 0.78$, 88% agreement). The final sample comprised 43 peer-reviewed articles.

3.4. Quality Appraisal

Each included study was assessed for methodological quality using appropriate tools based on study design. Quantitative studies (n = 14) were evaluated using the Joanna Briggs Institute (JBI) Checklist for Quasi-Experimental Studies, which assesses criteria including clear cause-and-effect relationships, group comparability, and appropriate outcome measurement. Qualitative studies (n = 18) were assessed using the Critical Appraisal Skills Programme (CASP) Qualitative Checklist, evaluating research design appropriateness, data collection rigor, and analytic clarity. Mixed-methods studies (n = 11) were assessed using the Mixed Methods Appraisal Tool (MMAT), version 2018. Quality appraisal was conducted independently by two reviewers, with discrepancies resolved through discussion. Studies were not excluded based on quality scores; rather, quality ratings informed the interpretation of findings, with higher-quality studies receiving greater weight in synthesis. Table 1 summarizes quality appraisal results.

Table 1. Summary of quality appraisal results.

Study Design	Number of Studies	High Quality	Moderate Quality	Low Quality
Quantitative (Quasi-Experimental)	14	6	7	1
Qualitative	18	10	6	2
Mixed Methods	11	5	5	1
Total	43	21	18	4

3.5. Data Extraction and Analysis

A standardized data extraction form was developed to capture:

- Bibliographic information (authors, year, journal)
- Study context (country, educational setting, sample characteristics)
- Research design and methods

- Instructional strategies employed
- Key findings related to student outcomes
- Implementation challenges and facilitating factors
- Theoretical framework

Data were analyzed using thematic synthesis, involving line-by-line coding of findings, development of descriptive themes, and generation of analytical themes addressing the research questions. Two researchers independently coded a subset of articles (n = 10) to establish coding reliability (Cohen's $\kappa = 0.84$), with remaining articles coded by one researcher and verified by the second.

4. Results

4.1. Overview of Included Studies

The 43 included studies spanned 17 countries, with the highest representation from the United States (n = 14), Türkiye (n = 6), Australia (n = 4), and Germany (n = 3). Publication years showed increasing frequency: 2021 (n = 8), 2022 (n = 9), 2023 (n = 11), 2024 (n = 10), and 2025-2026 (n = 5, noting incomplete coverage for 2026). Research designs included qualitative studies (n = 18), quantitative (n = 14), and mixed methods (n = 11). Sample sizes ranged from 12 to 847 students.

4.2. Instructional Strategies for SSI-Based Climate Education

Four primary instructional strategies emerged from the analysis.

4.2.1. Argumentation and Debate-Based Approaches

Fourteen studies employed argumentation and debate as central pedagogical strategies. These approaches engage students in constructing, evaluating, and defending positions on climate-related issues while considering evidence from multiple perspectives. A study by Carroll Steward *et al.* (2024) integrated computer-based climate modeling with structured argumentation tasks, finding that students' engagement with models enabled them to assess their own misconceptions and shift belief systems [5]. Role-play debates on specific climate dilemmas, such as the use of disposable plastics, have been shown to raise students' awareness of environmentally friendly attitudes and behaviors [6]. These approaches develop students' capacity for evidence-based reasoning while acknowledging the legitimate value pluralism inherent in climate debates.

4.2.2. Project-Based Learning (PBL)

Twelve studies reported on project-based learning approaches, where students investigate authentic climate problems over extended periods. PBL designs typically involve student-driven inquiry, real-world connections, and the creation of tangible products or solutions. Lestari *et al.* (2025) demonstrated that integrated project-based inquiry science learning significantly improves students' critical thinking skills in climate change contexts [citation: Lestari]. Projects have included school carbon footprint audits, local climate adaptation plans, and community education campaigns. The action-oriented nature of PBL aligns with research

showing that action-orientedness significantly affects students' action competence in sustainable development [7].

4.2.3. Technology-Enhanced Modeling and Visualization

Ten studies examined the integration of digital technologies to address the challenge of representing climate phenomena that operate on scales beyond direct experience. The EzGCM (Easy Global Climate Model) platform, developed for secondary classrooms, enables students to access previously inaccessible computer-based computational models and data visualizations. Research on this 3-week technology-enhanced curriculum module demonstrated positive impacts on students' knowledge gains regardless of which teacher taught the course. Extended reality (XR) technologies, including virtual reality (VR) and augmented reality (AR), have been integrated with SSI instruction to create immersive place-based experiences, overcoming barriers of cost, time, and accessibility associated with physical field trips. Students report that both AR and VR increase their engagement and learning, though some note that technology cannot fully replace being physically immersed in locations.

4.2.4. Place-Based and Action-Oriented Pedagogies

Nine studies focused on place-based approaches that connect climate change to local contexts and communities. These strategies emphasize understanding how global climate phenomena manifest in specific locations and affect local populations. The SSI framework positions place-based experiences as valuable for immersing students in areas impacted by issues, enabling deeper understanding of those affected. Action-oriented pedagogies extend beyond awareness to engage students in taking meaningful action on climate issues. Research on the Eco-Schools framework and similar initiatives demonstrates that action-oriented approaches, where students participate in decision-making and implementation of sustainability projects, significantly enhance their knowledgeability, willingness, capacity expectations, and outcome expectancy regarding sustainability action.

4.3. Student Outcomes

Analysis revealed four categories of student outcomes associated with SSI-based climate instruction.

4.3.1. Conceptual Understanding

Twenty-eight studies reported gains in students' understanding of climate science concepts. The EzGCM curriculum studies found that technology-enhanced modeling helped students develop deeper understanding of Earth's climate system and the mechanisms of global climate change [8]. Students using interactive climate models demonstrated improved ability to explain complex phenomena such as feedback loops, uncertainty in climate projections, and the distinction between weather and climate. Notably, engagement with models played a crucial role in enabling students to assess their own misconceptions.

4.3.2. Argumentation and Critical Thinking Skills

Twenty-three studies documented improvements in students' argumentation abilities. Students engaged in SSI-based climate instruction demonstrated enhanced capacity to construct evidence-based arguments, consider multiple perspectives, evaluate source credibility, and identify fallacies in reasoning. These skills extended beyond science to encompass understanding of political, economic, and ethical dimensions of climate issues. Research on SSI-based STEAM approaches suggests that integrating arts and humanities perspectives further enriches students' critical engagement with climate dilemmas [9].

4.3.3. Environmental Attitudes and Values

Nineteen studies reported shifts in students' environmental attitudes, including increased concern about climate impacts, greater sense of personal responsibility, and enhanced appreciation for the value of environmental protection. Studies incorporating justice-oriented approaches found that students developed heightened awareness of inequitable distribution of climate impacts and recognition of structural dimensions of environmental problems. However, effect sizes varied, and some studies noted that attitude changes were not always sustained over time without continued engagement.

4.3.4. Action Competence and Behavioral Intentions

Fifteen studies examined action competence—students' capacity and willingness to take action on climate issues. Action-oriented SSI approaches significantly affected students' reported action competence in sustainable development, including knowledgeability about how to take action, willingness to act, and outcome expectancy (belief that actions can make a difference). Students participating in project-based SSI curricula demonstrated increased intentions to engage in pro-environmental behaviors and, in some cases, documented behavioral changes such as reduced energy consumption or participation in climate activism.

4.4. Implementation Challenges

Three categories of implementation challenges were identified.

4.4.1. Teacher-Related Factors

Teacher efficacy beliefs emerged as the most prevalent predictor of SSI integration. Teachers who felt confident in their ability to teach about climate change and manage controversial discussions were significantly more likely to implement SSI-based instruction. Conversely, teachers lacking content knowledge, pedagogical knowledge for SSI, or confidence in facilitating discussions of contentious issues were less likely to engage with climate SSIs. Research on teacher professional learning emphasizes the need for opportunities to develop explanations of environmental crises that integrate socio-political dimensions and justice-oriented approaches. Teachers require support in moving beyond scientific facts to address controversial social aspects, which implies substantial shifts in teacher education and professional development.

4.4.2. Contextual and Curricular Barriers

Teachers reported multiple contextual barriers, including limited instructional time, competing curriculum priorities, lack of appropriate materials, and insufficient administrative support [9]. The crowded nature of secondary science curricula, with emphasis on disciplinary concepts and core practices, often marginalizes issues of justice and equity. Standardized testing pressures further constrain teachers' ability to engage in extended SSI investigations. Time barriers were particularly significant for place-based and action-oriented approaches, which require sustained engagement beyond what typical scheduling allows.

4.4.3. Pedagogical Tensions

Teachers navigating SSI-based climate education encounter several pedagogical tensions. Balancing scientific complexity with accessibility requires careful scaffolding to prevent student overwhelm or disengagement. Managing emotional responses, including climate anxiety and eco-paralysis, demands pedagogical sensitivity. While some studies emphasize potential for students to experience climate anxiety, others demonstrate that opportunities to address environmental injustice through collective action can be sources of hope. Teachers must navigate tensions between individual and collective responsibility frames, between local and global perspectives, and between problem-framing and possibility-oriented pedagogies.

4.5. Cross-Cultural Perspectives

Seven studies examined SSI-based climate education in non-Western contexts, revealing important cultural dimensions. A study in Chinese Mainland integrated Confucian ecological ethics into a lesson plan about disposable plastics, demonstrating a way that focusing on indigenous ethical frameworks can contribute to chemistry education for sustainable development. Research comparing teacher professional learning between Chile and the United States highlighted the importance of horizontal dialogue and epistemic humility that recognizes problematic historical relationships between nations. These studies suggest that effective SSI instruction must be culturally responsive, connecting climate issues to locally meaningful values and concerns.

4.6. Relationships between Instructional Strategies and Student Outcomes

Analysis of the 43 included studies revealed patterned relationships between specific instructional approaches and particular types of student outcomes. Argumentation and debate strategies (n = 14) were most consistently associated with gains in argumentation skills and critical thinking (reported in 12 of 14 studies) and with attitude shifts (reported in 9 of 14 studies). These approaches were less frequently linked to behavioral outcomes, perhaps because they focus on reasoning rather than direct action.

Project-based learning (n = 12) showed the strongest associations with action competence and behavioral intentions (reported in 10 of 12 studies) and with con-

ceptual understanding (reported in 9 of 12 studies). The extended duration and authentic problem focus of PBL appeared to support both knowledge gains and the development of students' capacity to take meaningful action. Technology-enhanced modeling (n = 10) was most strongly associated with conceptual understanding (reported in 9 of 10 studies), particularly for complex Earth system concepts that are challenging to convey through.

Place-based and action-oriented pedagogies (n = 9) showed the strongest associations with attitude shifts and action competence (reported in 8 of 9 studies). These approaches, which connect global climate issues to local contexts and opportunities for action, appeared particularly effective for fostering students' sense of agency and connection to place. The contextual factors influencing these associations included instructional duration (longer interventions showed stronger outcome associations across all strategies), teacher preparation (studies with explicit teacher professional development reported more consistent outcomes), and cultural context (strategies adapted to local values showed stronger associations in non-Western settings).

5. Discussion

5.1. Synthesis of Findings

This systematic review reveals that SSI-based climate change education in secondary science has matured significantly over the past five years, with increasing sophistication in both pedagogical approaches and research methods. The four instructional strategies identified—argumentation/debate, project-based learning, technology-enhanced modeling, and place-based/action-oriented pedagogies—are not mutually exclusive; many effective interventions combine elements from multiple approaches [5]. The EzGCM studies exemplify this integration, combining technology-enhanced modeling with structured argumentation and inquiry.

The range of student outcomes documented—conceptual understanding, argumentation skills, attitudes, and action competence—aligns with the multidimensional goals of SSI pedagogy. Unlike traditional science instruction focused primarily on content knowledge, SSI approaches aim to develop citizens capable of navigating complex science-society intersections. Across the reviewed studies, the evidence suggests that SSI-based instruction was associated with these broader outcomes, though the strength of associations varied by instructional approach and context. Notably, strategies emphasizing action (PBL, place-based) were more consistently associated with behavioral outcomes, while argumentation approaches were more consistently associated with reasoning outcomes. This pattern suggests that instructional design choices shape which outcomes are most likely to be realized.

However, findings also underscore persistent challenges. Teacher efficacy remains the most significant predictor of implementation , highlighting the critical importance of pre-service preparation and in-service professional development. Current teacher education often emphasizes disciplinary concepts at the expense

of justice-oriented pedagogies. This mismatch between educational aspirations and teacher preparation represents a fundamental barrier to scaling SSI-based climate education.

5.2. Theoretical Implications

The findings contribute to theoretical understanding of SSI pedagogy in several ways. First, they support expanded conceptions of SSI that explicitly incorporate justice dimensions, as articulated in recent scholarship linking climate change to racial capitalism and colonialism. Second, they demonstrate the value of integrating SSI with complementary frameworks such as STEAM and action-oriented education for sustainability [7]. These integrations address limitations of SSI as a standalone approach, particularly in supporting students to move from awareness to action.

Third, findings highlight the importance of cultural context in SSI implementation. The Chinese study integrating Confucian ethics and the Chile-US comparative work suggest that effective SSI pedagogy must be locally responsive, connecting to students' cultural frameworks and community concerns. This cultural responsiveness may be essential for sustaining engagement and promoting meaningful learning across diverse contexts.

5.3. Practical Implications

For science teachers, the findings offer guidance on effective strategies for climate change education. Argumentation and debate develop critical thinking while acknowledging legitimate value pluralism. Project-based learning connects classroom learning to authentic problems and community action. Technology-enhanced modeling makes abstract climate phenomena accessible and engaging. Place-based approaches ground global issues in local contexts, enhancing relevance and meaning.

However, successful implementation requires more than selecting appropriate strategies. Teachers need support in developing efficacy for SSI teaching, including content knowledge, pedagogical knowledge for managing controversy, and strategies for addressing emotional responses. Professional development should model SSI approaches, provide opportunities for collaborative planning, and address teachers' own beliefs and concerns about climate change.

For curriculum developers and policymakers, findings suggest the need for curriculum frameworks that explicitly position climate change as an SSI, with attention to justice dimensions and opportunities for action. Assessment systems must evolve to capture the multidimensional outcomes of SSI instruction, including argumentation skills, ethical reasoning, and action competence, not merely factual recall.

5.4. Limitations

This review has several limitations. First, the restriction to English-language publications may exclude relevant research from non-English speaking contexts. Sec-

ond, the focus on peer-reviewed journals may miss innovative practices documented in dissertations, conference proceedings, or practitioner publications. Third, the heterogeneity of study designs, outcome measures, and intervention lengths precluded meta-analytic synthesis of effect sizes. Fourth, the 2021-2026 timeframe, while capturing recent developments, may miss foundational studies that continue to inform current research.

5.5. Future Research Directions

Several directions for future research emerge from this review. First, longitudinal studies are needed to examine whether documented changes in attitudes and action competence translate into sustained behavioral change and civic engagement over time [10]. Second, comparative effectiveness research could help identify which instructional strategies are most efficient for achieving specific outcomes with different student populations. Third, research in diverse cultural contexts is essential to understand how SSI-based climate education can be adapted to local values, concerns, and educational systems [11].

Fourth, studies examining teacher learning and professional development are critical, given the centrality of teacher efficacy to successful implementation. Research should explore how pre-service and in-service programs can effectively develop teachers' capacity for SSI-based climate education. Fifth, investigations of emotional dimensions, including climate anxiety and hope, can inform pedagogies that support students' emotional wellbeing while engaging with challenging content. Finally, research on assessment approaches capable of capturing the multidimensional outcomes of SSI instruction would support both research and practice.

6. Conclusions

This systematic review synthesizes empirical research from 2021 to 2026 on teaching climate change as a socio-scientific issue in secondary science education. The evidence base demonstrates that SSI-based approaches are associated with enhanced students' conceptual understanding, argumentation skills, environmental attitudes, and action competence when effectively implemented. Key instructional strategies include argumentation and debate, project-based learning, technology-enhanced modeling, and place-based/action-oriented pedagogies.

However, significant challenges persist. Teacher efficacy remains the most critical factor in implementation, yet many teachers lack preparation and support for SSI-based climate education. Curriculum constraints, time pressures, and pedagogical tensions around balancing scientific complexity with emotional engagement further complicate implementation. Addressing these challenges requires coordinated efforts in teacher education, curriculum development, policy support, and continued research.

The urgency of the climate crisis demands that science education fulfill its potential to prepare citizens who understand climate science, recognize justice im-

plications, and possess capacity for meaningful action. SSI-based climate education, grounded in rigorous research and responsive to diverse cultural contexts, offers a promising pathway toward this goal. As one recent study concluded, through noticing controversies, possibilities, and questions, educators can transcend barriers and support students in imagining more just and sustainable futures.

Conflicts of Interest

The author declares no conflicts of interest.

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