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Transforming education for a sustainable future: an analysis of teacher education in the context of climate change

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In the specific context of geography and science teachers' training, socio-environmental problems, including climate change, highlight the need for professional development that facilitates the integration of social and environmental dimensions in favor of sustainability. This perspective seeks to promote wellbeing for all within planetary limits. This article addresses key questions: how has teacher education been structured to address climate change? What topics, methodologies and strategies have been used in this training? Where are documented research studies located on the disciplinary/transdisciplinary spectrum? This study will present the main results and knowledge derived from bibliographic research carried out in accordance with the Prisma 2020 protocol, aimed at identifying trends, challenges and good practices in education for sustainability. The results reveal multiple perspectives, contents, strategies and methodologies that enable us to determine the existence of a gradient ranging from disciplinary perspectives of climate sciences to interdisciplinary approaches that glean knowledge from several disciplines, such as ecology, economics and social sciences. In addition to a broader perspective of climate change, involving not only scientific knowledge, but also local and indigenous knowledge and associated ethical and moral perspectives, which bring these approaches closer to the transdisciplinary perspective.

KEYWORDS

sustainability, teacher education, socio-environmental, science education, climate change education

1 Introduction

The professional development of teachers in areas such as science and geography face significant challenges in addressing socio-environmental issues, especially climate change. This phenomenon, which transcends disciplinary boundaries, demands an education that integrates economic, social and environmental dimensions of sustainability, oriented toward general wellbeing within planetary boundaries (Maass et al., 2022; Richter-Beuschel and Bögeholz, 2020; UNESCO, 2020; IPCC, 2023). This has been acknowledged by international bodies, such as UNESCO, highlighting the importance of inclusive climate

education that prepares teachers not only to teach about climate change, but to facilitate understanding and commitment to sustainability in their students (Walsh, 2012).

Science education has evolved to include not only basic science literacy, but also critical science literacy that promotes competencies for social transformation (Dillon and Avraamidou, 2020; Sjöström and Eilks, 2018; Sjöström, 2024). In the context of climate change, this approach suggests a switch from science for all (Perspective II) to critical literacy (Perspective III), which integrates political, social, reflective and collaborative dimensions. This teaching framework also includes the need to adapt to local contexts and to foster a deep and multidimensional understanding of the context in students, of schools and their communities [Profesores Reflexionando por una Educación Transformadora en Ciencias (PRETEC), 2019; Guerrero et al., 2024; Guerrero and Olave, 2020; Marzábal and Merino, 2021].

The concept of climate literacy, defined as understanding the reciprocal influence between climate and society, is central to effective climate education (Dupigny-Giroux, 2010; Kumar et al., 2023). According to Eze et al. (2022), a climate-literate person not only understands the essential principles of the Earth's climate system but is also able to critically analyze and evaluate scientific and non-scientific climate information, fostering informed and responsible decisions. Approaches to climate change from a standpoint exclusively focused on climate science, which do not explicitly integrate the social, economic, emotional and environmental dimensions, limit the complex and holistic understanding of climate change and its multiple facets.

Various approaches have highlighted the importance of education that goes beyond scientific and technical aspects, toward a perspective of social and political action. Reis (2020) proposes that science education should evolve toward an approach of social activism, empowering students to become agents of change and collaborate in the search for collective solutions to 21st century challenges. This perspective, supported by Kanios and Weissbrot-Koziarska (2024), not only fosters the development of scientific competencies, but also cultivates active and committed citizens, capable of influencing political decisions and transforming their communities. In this context a holistic epistemological perspective makes sense, Marg and Theiler (2023) highlight the value of transdisciplinarity in solving problems of "social interest," and point out that pressure is thereby exerted on the limits of scientific research regarding which actors are producers are producers of valid knowledge. Transdisciplinarity is the co-production of knowledge that transcends disciplinary, academic, and epistemic boundaries (Thompson et al., 2017; Dedeurwaerdere, 2024). Broadly speaking, Transdisciplinarity approaches problem fields in such a way that it can: (a) capture the complexity of problems, (b) take into account the diversity of scientific and life-world perceptions of problems, (c) link abstract and case-specific knowledge, and (d) develop knowledge and practices that promote what is perceived as the common good [...] (Pohl and Hirsch Hadorn, 2007).

Climate change education poses a multidimensional challenge for teachers, who must address both the scientific complexity of the topic and its social, political, and ethical implications. Brey et al. (2015) highlight that, regardless of the methodological approach or its scale, climate change represents a challenge in teacher training, requiring specific preparation that includes advanced knowledge, critical skills and proactive attitudes toward sustainability. Seikkula-Leino et al. (2021) for his part, he points out that the idea of integrating environmental/sustainable education and entrepreneurship education could be promoted more explicitly in the future, with greater emphasis on these interdisciplinary educational topics in educational curricula and policies.

This study seeks to answer key questions to understand the state of teacher education on climate change: how has teacher training been conducted to educate on climate change? What topics, methodologies and strategies have been used in this training? Where is documented research located within the continuum of disciplinary/transdisciplinary perspectives? These questions serve as guidelines for a comprehensive review of the existing literature, enabling the identification of trends, approaches and gaps in the field of work, as well as the most advanced teacher education for sustainability.

To ensure a rigorous and comprehensive analysis, this study uses the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol as a methodological guideline. This scoping review enables the inclusion of a wide variety of perspectives and sources, encompassing empirical and theoretical studies providing innovative approaches or proposals for improvement in climate change education. Since it is based on PRISMA, the analysis ensures a systematization of the review process, facilitating the identification of good practices and promising educational approaches.

This systematic review aims not only to understand the current state of climate change education for teachers, but also to provide a solid foundation for future research and educational proposals. By identifying gaps in the literature and areas requiring improvement, the study will contribute to the design of professional development programs that respond to emerging needs in climate education. Furthermore, by highlighting transdisciplinary and critical literacy approaches, this research provides practical guidelines for the development of socio-environmental competencies in teacher training, fostering integrated and transdisciplinary climate education.

Finally, climate change and socio-environmental issues pose an unprecedented challenge for teacher training, requiring educational approaches that integrate science, sustainability and social action.

2 Method

The review and analysis were organized in phases. In the first phase, collaborative sessions were held to build a shared epistemological basis for guiding research toward a deep understanding of the central elements that underpin the development of a training method in Climate Change Education, integrated with the use of technologies. The relevance of this initial phase lies in the need to build a common approach, identifying and discussing key theoretical and methodological perspectives that underpin research in environmental and climate education.

The epistemological approach used in this study is based on a socio-constructivist perspective, which considers knowledge as a product under construction, influenced by the social

contexts and shared experiences of the participants (Lievens and Kenis, 2018). This framework allowed the research teams to collaboratively approach the formulation of meaningful research questions, which not only responded to scientific concerns, but also addressed real pedagogical issues in the field of climate education. This orientation toward partner constructivism provided a solid foundation for the creation of new research hypotheses and an opportunity for dialogue and continuous questioning, which enriched the process.

Phase two aimed at formulating and defining the research questions resulting from the discussions and reflections in the initial meetings. These questions were central to defining the scope and purpose of the research, focusing on three main areas: what aspects should be investigated to improve teacher training on climate change? What are the key questions that can guide this research? What methodological flow and tools are most appropriate for addressing these issues? These questions were addressed from a dynamic and open perspective, with each work session contributing to refining and adjusting the research aspects, reflecting the progressive nature of the process. Far from being an end product, the methodology used is considered a flexible tool that evolves in response to new knowledge and emerging perspectives.

2.1 Systematic review: rationale and justification

Systematic review was the method selected to consolidate and analyze the existing literature on teacher professional development in climate education. This approach was chosen because of its ability to provide a comprehensive and reliable summary of the literature, minimizing bias through a meticulous process of study selection and analysis.

The review process was designed following the principles of transparency and reproducibility, which are valued in fields where it is important to consolidate knowledge regarding emerging practices and theories. A review of theoretical and empirical studies that offered innovative perspectives and proposals for improvement was also included, providing a broad view of the current status of research on teacher training in climate education.

The choice of databases was a crucial step in ensuring the validity and relevance of the studies reviewed. The Scielo, Scopus, Web of Science (WoS), and ERIC databases, widely recognized for their coverage of high-quality academic literature in disciplines such as education, environmental science, and sustainability studies, were selected.

Google Scholar was also used to include government documents and relevant gray literature, thus expanding the scope of the review and enabling a comprehensive analysis of climate change education proposals and programs.

2.2 Inclusion and exclusion criteria

Strict inclusion criteria were established to ensure the timeliness and relevance of the review. Only articles published in the last 10 years were considered, ensuring that the review reflected the most recent trends and developments. Open access publications were prioritized, allowing for greater accessibility and dissemination of findings to wider audiences, including researchers, educators, and policymakers.

Keyword selection was a critical component in ensuring the relevance of chosen articles. Two search methods were used:

a) *Primary Search:* terms in Spanish, such as *Desarrollo Profesional Docente* y *Educación en Cambio Climático* (Professional Teacher Development and Climate Change Education), focusing on databases containing literature in Spanish and systematizing bibliographic sources in Latin America.
b) *Secondary Search*: English keywords, such as *Teacher Professional Development*, *Teacher Learning*, *In-Service Teacher,* and Climate *Change*, in global databases and Google Scholar, thus expanding access to international research and relevant government documents.

The Boolean operators [AND] and [OR] were applied to specify and combine terms, optimizing the relevance of the results obtained. This search strategy was designed to retrieve a range of studies covering different perspectives and contexts in climate education. The references were managed and organized in an Excel database, where a preliminary analysis of each document was carried out prior to its inclusion in the review. This step was critical to ensure that each reference met the inclusion criteria, and to facilitate the traceability of decisions. The selected articles were analyzed using the Atlas.ti.24 software, to perform a detailed coding of the data and facilitate the identification of recurring patterns and themes.

2.3 Systematization methodology: implementation of PRISMA 2020

The PRISMA 2020 model was adopted to structure the review process, providing a robust methodological framework that ensures transparency in documentation. PRISMA facilitates clear and detailed communication of each step of the article selection and screening process, allowing readers to understand the methodological decisions and the inclusion and exclusion criteria applied. The use of PRISMA ensures consistent and detailed documentation, which is essential for systematic reviews that need to be reproducible and verifiable. In this study, the PRISMA model was implemented through a flowchart (see Figure 1), which shows the identification, selection, eligibility and inclusion phases of articles, providing a visual representation of each stage of the review process (Page et al., 2021).

At the end of the review process, a final group of 33 documents selected for detailed and thorough review was compiled. This set of articles is a solid foundation of knowledge and pedagogical approaches that will provide recommendations for teacher education on climate change.

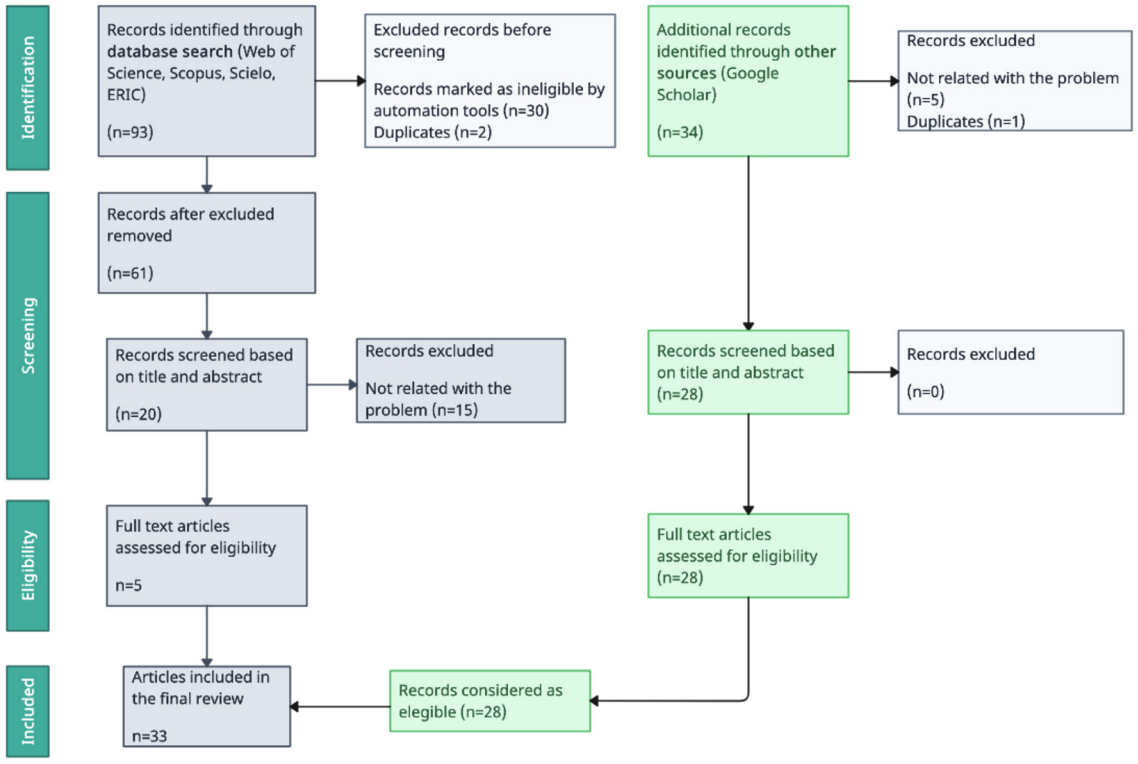

FIGURE 1
PRISMA 2020 flowchart (Source: created by the authors).

The Table 1 shows Eighty-nine codes organized into four main categories were identified in the analysis process: contents, Attitudes and Values, Strategies and Methodologies. Each of these categories relates to specific aspects of teacher professional development in the context of climate education. Details of each of these categories are given below:

a) Contents: refers to the central concepts addressed in the training processes analyzed. They include specific topics such as climate science, sustainability, and environmental policies.
b) Attitudes and Values: refers to the attitudes and values sought in the training programs analyzed, which include social-emotional competencies and ethical values related to climate education.
c) Strategies: refers to specific approaches and procedures during training processes, such as the use of school text, technology, or other.
d) Methodologies: refers to findings associated with mature, consolidated reference frameworks, such as collaborative work, Critical Thinking, etc. used for teaching and learning about climate change.

The quantitative results show that there is a higher concentration of research codes in the strategies and contents categories, than in methodologies, attitudes and values categories. These categories and codes were analyzed in a recurring procedure to identify errors and determine links and relationships between documents and concepts investigated. The detailed results are presented in the following section.

3 Findings

3.1. Key issues in climate change education

The literature review identified a number of recurring themes that are essential for teacher training on climate change. These topics not only reflect key concepts, but also emphasize the multidimensional and complex nature of climate education. Highlights include:

a) Climate adaptation, mitigation and resilience: many training programs focus on these three pillars as central components of climate education. Adaptation and mitigation are strategies that seek to prepare students to respond to current and projected climate changes, while resilience focuses on strengthening the capacity of students and their communities to withstand and recover from adverse weather events (Drewes et al., 2018; Reimers, 2021; Oranga et al., 2023). These issues are addressed from both a scientific and social perspective, underlining the importance of building leadership in young people who can make informed and effective decisions when faced with climate change challenges.
b) Food security, health, and displacement: climate change education addresses the broad and multisectoral impacts of climate change, such as declining food security, deteriorating health, and climate-induced displacement (Favier et al., 2021; Waldron et al., 2020). These issues highlight the unequal and political nature of climate change, where the most vulnerable populations are the most affected. Education in these

TABLE 1 Table shows the distribution of codes by category.

Categories	Number of codes	Examples the topic
Strategies	39	Field Work, Experiential Learning, CSS (controversy), Text support, Solution oriented, Action oriented…
Contents	25	Climate Science, greenhouse effect, climate and weather, political, social and economic causes, scientific fundations…
Methodologies	15	Inquiry Based, Play based Learning, critical Thinking, Collaborative Learning, Place based learning, creative thinking…
Attitudes and values	10	Values, ethics and moral obligations; Awareness of CC; Collective responsibility; Community development; Social activism…
Total	89	

aspects seeks to make students aware of the interconnection between climate and social dimensions, promoting a critical understanding of climate change as a social justice issue.

c) Historical and anthropogenic causes of climate change: the revised teacher education programs include a discussion of the causes of climate change, highlighting both natural and human causes, the greenhouse effect, and increased GHG emissions since the industrial revolution. This understanding allows teachers to explain the difference between climate and weather and explore how human activities have accelerated climate change (Drewes et al., 2018; Ramcilovic-Suominen et al., 2022).

d) Local and indigenous knowledge: an emerging theme in climate education is the recognition of traditional or local knowledge and indigenous worldviews, such as the medicine wheel, which symbolizes the interrelationship between life and the natural elements (earth, water, fire and air) (Nam et al., 2013). These traditional perspectives align with climate science by emphasizing the interdependence between Earth's systems and the flow of energy. Including this knowledge in training programs not only enriches climate education, but also reinforces the importance of respecting and valuing worldviews regarding life respectful of nature and in harmony therewith.

3.2. Attitudes and values in climate change education

The reviewed studies underline the importance of promoting the development of positive attitudes and pro-environmental values in teachers and students. Specifically:

a) Agency and Responsibility: studies such as the one by Babatunde et al. (2023) highlight the fact that one of the main barriers to teaching about climate change is lack of training and lack of interest in the subject. To counter this, the need for training programs that foster a sense of agency in students, i.e., the ability to act and respond to climate change in their own contexts, has been emphasized. Students' response to these challenges can, in turn, strengthen pro-environmental attitudes and teachers' collective responsibility (Drewes et al., 2018).

b) Critical Thinking Development: climate education aims to cultivate critical thinking through debate and reflection on environmental challenges Das Malakar et al. (2024) argues that this approach enables students not only to understand the science of climate change, but also to analyze its social and economic impacts, to focus on solutions and to train children and youth as future climate leaders. By fostering transformative learning, students are prepared to design and execute mitigation and adaptation strategies, strengthening their capacity to make informed and responsible decisions (Eze et al., 2022; Ojala, 2023; Songqwaru and Tshiningayamwe, 2021).

c) Emotional and Social Competencies: climate change training programs recognize that this topic can generate anxiety and concern in students. Hence, the development of emotional competencies that allow students to manage their emotions constructively has been promoted. This approach also requires the development of social skills, such as communication and collaboration, which are essential for teamwork and collective action in mitigating climate impacts (Babatunde et al., 2023; Demant-Poort and Berger, 2021; Drewes et al., 2018; Herrick et al., 2025; Lozano et al., 2022).

3.3. Strategies and methodologies in teacher training for climate change

Climate education requires methodologies and strategies that address the complexity of the issue. The most salient include:

a) Collaborative learning and communities of practice: collaborative learning in face-to-face and virtual professional communities is a key strategy for teacher professional development. This methodology allows teachers to share ideas, resources and experiences, strengthening collective responsibility and a proactive approach to climate change (Liu and Roehrig, 2019; Waldron et al., 2020). Practice communities, on the other hand, refer to groups of people who share an interest, concern or passion for a topic related to teaching and learning, and who interact on a regular basis to deepen their knowledge, improve their practices and generate meaningful learning together. These types of communities facilitate pedagogical accompaniment, which is fundamental for the success of any kind of training (Johnson et al., 2008). This is reaffirmed by Ben Zvi Assaraf et al. (2024) who emphasizes the importance of teaching competencies in collaboration and the development of relevant teaching materials.

b) Interdisciplinary and place-based approaches: interdisciplinary and place-based approaches enable students to understand climate vulnerabilities from a holistic perspective (Armstrong and Krasny, 2020; Favier et al., 2021; Songqwaru and

Tshiningayamwe, 2021). These approaches integrate school scientific research and the use of technology to address culturally relevant issues, recovering local and indigenous knowledge and developing local responses to climate challenges (Liu and Roehrig, 2019; Nam et al., 2013; Bascopé et al., 2025).

c) Active methods and experiential learning: active learning strategies, such as fieldwork, experiments and research projects, allow students to apply theoretical knowledge in real situations, developing personal and social skills (Favier et al., 2021; Bascopé et al., 2025). These hands-on activities foster student engagement and interest, and strengthen their ability to research, communicate, and act effectively on climate issues (Jeong et al., 2021; Johnson et al., 2008; Li and Krasny, 2019).

d) Immersive experiences: immersive experiences are consecutive days of teacher training and professional development, in person, in a natural environment. They are usually camps or seminars in which participants interact for several days, generating affective and professional bonds between them. Designing immersive learning experiences allows students to apply their knowledge in real contexts, developing practical skills and competencies for climate action (Drewes et al., 2018).

3.4. Specific strategies for classroom implementation

The reviewed studies identified several specific strategies for the implementation of climate education in the classroom. These strategies seek to make learning meaningful, practical and aligned with local issues. Some of the most relevant are:

a) Specialized educational resources: climate change learning modules, including key scientific concepts and practical activities designed to promote critical thinking and reflective analysis (Favier et al., 2021; Li and Krasny, 2019; Thenga et al., 2021).

b) Experiential Activities: fieldwork and research projects allow students to experience and contrast theoretical knowledge with reality (Favier et al., 2021; Li and Krasny, 2019; Songqwaru and Tshiningayamwe, 2021). These activities also foster the development of social and personal competencies, such as collaboration and social responsibility (Favier et al., 2021)

c) Reflective learning: promoting discussion and problem-solving through reading, workshops, and reflective activities fosters the development of critical thinking and decision-making for innovative practice (Corner et al., 2015; Eze et al., 2022; Ojala, 2012; Songqwaru and Tshiningayamwe, 2021).

3.5. Disciplinary/transdisciplinary continuum in climate change education

The analysis of the reviewed studies reveals a continuum of approaches ranging from strictly disciplinary to fully transdisciplinary, reflecting the epistemological and methodological diversity in climate change education. This section deepens the discussion of this continuum by providing concrete examples of its implementation in teacher training programs, thereby reinforcing the connection between theoretical frameworks and educational practice.

a) Disciplinary Approach. At the disciplinary end of the continuum, climate change education focuses on specific scientific concepts such as the greenhouse effect, the carbon cycle, and global weather patterns (Drewes et al., 2018; Thenga et al., 2021). This approach is grounded in formal scientific knowledge and aims to promote a rigorous understanding of the mechanisms underlying climate change. Applied example: in initial teacher training programs in natural sciences, such as those reported by Drewes et al. (2018), experimental teaching sequences are used that include laboratory simulations and analysis of real climate data to strengthen future teachers' scientific competencies, particularly in understanding Earth's energy balance.

b) Interdisciplinary Approach. The interdisciplinary approach combines knowledge from various disciplines—such as ecology, economics, and social sciences—to construct a more integrated understanding of the causes and consequences of climate change (Favier et al., 2021; Johnson et al., 2008). This perspective enables the linkage of natural and human systems and fosters the development of skills to analyze problems from multiple angles. Applied example: Favier et al. (2021) document a European teacher education program where interdisciplinary projects are designed based on regional case studies. Preservice teachers develop pedagogical proposals that integrate mathematical modeling of emissions, economic analysis of environmental policies, and the social implications of climate-induced displacement.

c) Transdisciplinary Approach. At the transdisciplinary end, climate change education incorporates not only scientific and technical knowledge but also local and ancestral knowledge (Roehrig et al., 2012), integrating ethical, cultural, and emotional dimensions of the climate crisis (Jeong et al., 2021; White et al., 2014). This approach aims to cultivate student agency, transformative action, and active participation in mitigation and adaptation processes (Corner et al., 2015; Demant-Poort and Berger, 2021; Fage-Butler, 2022; Tolppanen et al., 2022; Dedeurwaerdere, 2024). Applied example: in the program documented by Roehrig et al. (2012), preservice teachers co-design educational projects with Indigenous communities to address local challenges such as drought or biodiversity loss. These experiences enable future teachers to bridge formal curricula with sustainable territorial practices and to develop participatory methodologies focused on climate justice.

These approaches should not be viewed as mutually exclusive, but rather as complementary possibilities that can be articulated depending on training contexts and educational goals. The progressive incorporation of inter- and transdisciplinary elements in teacher education expands pedagogical capacities to address the complexity of climate change through a critical, situated, and inclusive lens.

4 Discussion

The findings of this systematic review on climate change education in teacher education reveal key dimensions that need to be considered to improve and strengthen the preparation of educators in this area. The key aspects of the results are examined below, and eight relevant insights emerging from the analysis are presented.

4.1. Importance of comprehensive education that addresses adaptation, mitigation and resilience

Integrating the concepts of adaptation, mitigation and climate resilience into curricula is critical, as it allows teachers to understand and address the various dimensions of the climate crisis. The results highlight the fact that these concepts must be treated from a practical and applied perspective, focusing on how teachers can prepare their students to act on the causes and effects of climate change in their own communities. However, in practice, training programs often focus mainly on scientific content, leaving aside the implementation of practical adaptation and mitigation strategies. This suggests the need to incorporate specific modules that allow teachers to develop projects and activities that promote climate action at the local level.

4.2. Need to include local and indigenous knowledge in climate education

The recognition of ancestral and indigenous knowledge is a principal component in climate education, since this knowledge offers comprehensive insight into the relationship between human beings and the environment. Indigenous communities, with their ancestral knowledge, or knowledge associated with local customs, have developed an in-depth understanding of climate patterns and environmental impacts in their territories, which is a valuable source for learning, whereas local practices and customs allow them to contribute to designing pathways for adaptation to climate change. Including this knowledge in teacher education programs not only enriches curricular content, but also promotes respect for cultural diversity and strengthens the bond between students and their local contexts.

4.3. Development of critical thinking and the ability to make informed decisions

Climate education should encourage students and teachers to develop critical skills for analyzing and assessing scientific and non-scientific climate information. This is essential in a context where misinformation and simplistic narratives about climate change can divert attention from the real problems and possible solutions. Training programs must promote activities that encourage critical thinking, such as debates, case studies and analysis of scientific controversies identified by them, in order to develop and guide their students in making informed and responsible decisions.

4.4. Importance of emotional and social competencies to address climate anxiety

The climate crisis generates intense and sometimes overwhelming emotions, such as anxiety, fear and helplessness. The results suggest that training programs should include emotional education components that allow teachers and students to manage these emotions constructively. Emotional competencies, such as empathy and emotional resilience, help students feel empowered to act, rather than being paralyzed by the magnitude of the problem. At the same time, developing soft skills, such as collaboration and communication, is critical to tackling climate change collectively and effectively.

4.5. Focus on collaborative learning and creating practice communities

Collaborative learning and the development of practice communities among teachers are key strategies for strengthening climate education. The results show that teamwork and collaboration between teachers enable the sharing of resources, experiences and good practices, creating an environment of mutual learning and continuous support. These practice communities are especially valuable in the context of climate education, where teachers may feel isolated or overwhelmed by the complexity of the topic. Educational institutions should encourage and support the development of these communities as an integral part of teacher professional development.

4.6. Use of interdisciplinary and place-based strategies

Climate education benefits from interdisciplinary and place-based approaches, which enable students to understand how climate change affects their own communities and local contexts. Place-based approaches foster students' connection to their environment and promote a deeper understanding of environmental issues specific to their regions. Interdisciplinary strategies also combine perspectives from diverse areas of knowledge, such as science, economics, geography, arts and ethics, offering a comprehensive view of the climate crisis and possible solutions.

4.7. Implementation of active methods and immersive experiences in teaching

Active learning strategies and immersive experiences, such as fieldwork, experiments, and research projects, are essential for

students to understand and apply the knowledge gained in real-world situations. Active methods, such as problem- and project-based learning, enable students to engage in practical ways and develop competencies to act in the face of climate change. These hands-on experiences also foster the development of skills such as research, communication, empathy and leadership, which are critical to addressing climate challenges.

4.8. Need for a transdisciplinary education that integrates science and social action

Finally, the results show that climate change is such a complex phenomenon that it cannot be addressed from a single discipline. A transdisciplinary education enables combining scientific knowledge with moral, ethics, social, cultural and emotional aspects, fostering a holistic understanding of climate change. This transdisciplinary approach, which integrates social action and activism, helps students see climate education not only as an academic discipline, but as a tool for social change. Training institutions should foster a transdisciplinary approach to teacher education to ensure that future teachers can address climate change from a holistic, action-focused perspective.

We recover the main ideas of this review that allow readers of this article to visualize possible uses for teacher training. From the discussion of the results, eight key ideas:

a) Incorporate adaptation, mitigation and resilience as pillars in teacher training: programs must integrate these concepts in a practical way so that teachers can prepare their students to face the effects of climate change locally and globally.
b) Valuing and using local and indigenous knowledge in the climate change curriculum: recognizing and applying ancestral indigenous knowledge provides a valuable and culturally relevant perspective that enriches the understanding of the relationship between human beings and the environment.
c) Encourage critical thinking and informed decision making: climate education should equip students and teachers with skills to analyze and evaluate information critically, preparing them to deal with misinformation and make responsible decisions.
d) Develop emotional and social competencies to manage climate anxiety: addressing emotions associated with climate change is essential for students and teachers to transform anxiety into proactive action.
e) Promote collaborative learning and practice communities: institutions should foster collaboration among teachers, creating support networks where they can share resources, strategies and experiences in teaching climate change.
f) Use interdisciplinary and place-based approaches to contextualize climate change: these approaches help students connect climate change to their own environment and understand its impacts from different disciplines and perspectives.
g) Implement active methods and immersive experiences to facilitate learning: practical experiences, such as fieldwork and projects, enable students to apply knowledge in real contexts, strengthening their competencies to act in the face of climate change.
h) Adopt a transdisciplinary education that integrates, at least, science and social action: an education that combines scientific knowledge with moral, ethics and social action empowers students to address climate change holistically and become agents of change in their communities.

5 Conclusion

The guiding questions of this systematic review can be answered by analyzing the literature on teacher training in climate change. The conclusions reflect the advances, challenges and areas of opportunity to structure training programs that integrate the complexities inherent in climate change from various disciplinary and transdisciplinary perspectives. Below are the conclusions based on each question posed.

How has teacher training been structured to address climate change?

Teacher training in climate change, as presented in the reviewed literature, is predominantly structured in programs that integrate basic scientific knowledge regarding climate and climate change, including topics such as the greenhouse effect, greenhouse gas emissions and the environmental and social impacts of this phenomenon. However, there are significant limitations in terms of the integration of practical competencies and skills for climate action, as well as in the development of the social and emotional skills necessary for addressing the complexity of the problem. The structure of these training programs generally follows a sequential and disciplinary approach, which begins with an introduction to scientific fundamentals and advances toward the application of knowledge in educational contexts. However, as awareness of the importance of comprehensive climate change education increases, some programs are evolving to include social action components, where teachers lead climate adaptation and mitigation initiatives in their school communities.

What topics, methodologies and strategies are used in teacher training?

Central issues in teacher training to address climate change include adaptation, mitigation, and climate resilience. These issues reflect the need to prepare teachers to understand and teach the various aspects of climate change, from scientific causes to socio-economic and environmental impacts. Other issues emerging in the literature are climate justice, the role of public policies in climate action, and the importance of traditional and indigenous knowledge in understanding and responding to climate change. In terms of methodologies, climate change education benefits from active and collaborative approaches, such as problem-based learning, action-oriented, and place-based learning, which encourage students' active participation and connection to the local environment. The importance of creating practice communities among teachers is also highlighted, since they enable the exchange of experiences and the development of effective pedagogical strategies for teaching about climate change.

Specific strategies for teaching climate change include the use of learning modules on key concepts, activities outside educational establishments such as fieldwork, the use of experiments, and the encouragement of debate and reflection on controversial issues. These strategies not only seek to transmit knowledge, but also

to develop research, critical thinking, and social action skills in students.

Where are documented research studies located on the disciplinary/transdisciplinary spectrum?

Research in teacher training for climate change covers a disciplinary/transdisciplinary spectrum. At the disciplinary end, we find studies that focus exclusively on the teaching of scientific concepts of climate change, such as the Earth's climate system and the interactions between its components (atmosphere, hydrosphere, biosphere and geosphere). These disciplinary approaches are valuable in establishing a solid scientific foundation, but often lack an integrative perspective that allows teachers to address climate change from a more holistic approach. At the interdisciplinary level, research combines knowledge from different disciplines, such as environmental science, economics, politics, and ethics, to provide a more complete understanding of the causes and consequences of climate change. This approach is effective in teaching teachers to consider the multiple factors that influence climate change and to integrate different perspectives into their educational practices.

Finally, in the transdisciplinary approach, the most advanced research seeks to integrate scientific knowledge with local and indigenous knowledge and the moral and ethical perspective of the problem to promote education toward social action. This transdisciplinary approach is oriented toward the training of teachers who teach about climate change, fostering in their students the commitment and responsibility to face this global crisis from their own contexts. Transdisciplinarity in climate education allows teachers to guide their students in making informed decisions and implementing concrete actions for climate adaptation and mitigation, promoting active and responsible citizens.

Author contributions

RM-A: Conceptualization, Data curation, Formal analysis, Writing – original draft. AA: Funding acquisition, Resources, Writing – review & editing. DC: Investigation, Writing – review & editing. MB: Supervision, Validation, Writing – original draft. DS: Methodology, Writing – review & editing. RB: Supervision, Writing – review & editing. JS-P: Formal analysis, Writing – review & editing. CM: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Gen AI was used in the creation of this manuscript. The use of generative artificial intelligence (AI) in the preparation of this manuscript has been fundamental in optimizing the writing process and ensuring the quality of the content. Below are the reasons that justify its application: 1. Efficiency in research: Generative AI has facilitated the collection and synthesis of relevant information on complex topics, such as teacher training in the context of climate change. This has allowed the author(s) to access a wide variety of sources and perspectives in a reduced timeframe. 2. Improvement of writing: AI has contributed to enhancing the clarity and coherence of the text by suggesting structures and formulations that enrich the presentation of ideas. This is especially important in an academic manuscript, where precision and rigor are essential. 3. Idea generation: AI has served as a creative tool, offering suggestions for innovative approaches and methodologies that may not have been initially considered by the author(s). This has broadened the scope of analysis and discussion in the manuscript. 4. Review and correction: AI has assisted in reviewing the text, identifying grammatical and stylistic errors that may have gone unnoticed. This ensures a higher level of quality in the final manuscript. 5. Transparency and responsibility: By explicitly declaring the use of generative AI, the author(s) demonstrate their commitment to transparency in the research and writing process. This allows reviewers and readers to better understand the tools used in preparing the document. In conclusion, the use of generative AI has been a strategic decision to improve the quality, efficiency, and creativity of the manuscript, ensuring that it meets the academic standards required for publication. The author(s) assume full responsibility for its use and for the final content presented.

Publisher's note

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