CLIMATE CHANGE EDUCATION: THE PAST, PRESENT PUBLICATION TRENDS AND FUTURE RESEARCH AGENDA

Abstract

Climate Change Education (CCE) has developed as a critical field for promoting climate literacy, resilience, and sustainable behaviour among global communities. Despite various bibliometric studies on environmental education and climate change, there is still a lack of comprehensive longitudinal studies, particularly on CCE. This study closes the gap by undertaking a quantitative bibliometric analysis of CCE using three-decade Scopus publications, looking at productivity, social networks, and co-occurrence networks. The bibliometric analysis of CCE highlights a rapidly evolving field marked by high levels of collaboration, citation impact, and an accelerating publication trend, particularly since 2017. The most recent quinquennium (2020-2024) accounts for nearly 62% of all articles on the subject, indicating a surge in research interest and likely greater financing for CCE research. The high increase in publications from 2022 (36 articles) to 2024 (71 articles) shows an almost 100% increase in two years, demonstrating an exceptional spike in research focus on CCE. This indicates both a growing awareness of CCE's importance and likely increased research funding in response to global climate challenges. The analysis reveals that CCE research is multi-disciplinary and trans-disciplinary, encompassing not only environmental education but also the integration of technological, psychological, and sociocultural dimensions that collectively enrich the pedagogical landscape. This study provides a resourceful academic foundation for expanding CCE as a transformational research area in global education policy and practice.

Keywords: Bibliometric analysis, Climate literacy, Climate justice, Teacher education, Environmental education.

INTRODUCTION

Climate change is one of the vital issues that humanity faces today [1]. It is acknowledged as a very complex global issue [2], affecting practically every element of human and biological systems, with certain regions experiencing increased danger. Countries where agriculture is the major economic driver are especially susceptible, since climate change may seriously impact food production and economic stability [3]. Climate change is increasingly considered not merely as an environmental concern, but also as a security threat, given its ability to stymie national growth, worsen socioeconomic gaps, and fuel resource conflicts. In light of recent catastrophic weather occurrences, policy frameworks have begun to approach climate-related risks as vital to national security, tying climate discourse to wider agendas connected to anthropogenic dangers [4].

Education has emerged as an important instrument for addressing the urgency of climate change. Universities, in particular, play an important role in CCE, preparing future leaders to make educated, sustainable decisions [5],[6]. Effective climate education goes beyond individual action, influencing public perception and cultivating a culture that incorporates climate mitigation activities into both professional and personal realms. As a result, climate change has prompted a rethinking of formal education, urging a focus on sustainability and cross-disciplinary

collaboration to address scientific, social, environmental, and political problems [7], [8]. While climate change is a global issue that requires international collaboration, CCE is still under-represented in formal school curricula across the world [9], because there are few standardized climate education programs, knowledge and understanding of climate change are sometimes restricted to the efforts of dedicated individuals or isolated projects, rather than being integrated into educational systems [10]. As a result, there is an urgent need for a comprehensive and coordinated approach to CCE at all educational levels.

LITERATURE REVIEW

Climate change is one of the most important global concerns of the twenty-first century, having far-reaching implications for both human society and natural ecosystems. Despite substantial scientific data emphasising the need of reducing greenhouse gas emissions, societal activities are insufficient to fulfil global climate objectives [11]. Understanding the complex interactions between climatic systems and human activities is an important aspect of climate literacy. For example, polar areas are important climate change indicators, providing insights on global warming patterns and their larger implications [12]. However, public understanding of these scientific ideas is frequently insufficient, emphasising the need for increased civic science literacy and public awareness activities [13]. Enhancing scientific literacy not only improves understanding of climate change, but it also promotes informed decision-making and civic involvement [14]. Climate change is a worldwide problem and one of the main key term(s) that may attract numerous disciplines of research to be conducted. Assessing its changes through other methods of analysis, such as bibliometrics, demonstrates the need of taking into account its worldwide consequences [15].Adoption of social media has sped up content creation and distribution, enabling the discussion of crucial topics like climate change and sustainability [16]. Artificial intelligence (AI) is seen as a critical component in addressing the agriculture sector's present concerns, which include food production and climate change [17]. The sustainability transitions investigation has emerged as a viable strategy to managing climate change-related uncertainties [18].

In addition to scientific education, multidisciplinary approaches are widely seen as critical for addressing the numerous difficulties faced by climate change. Because environmental, social, and economic systems are interrelated, joint efforts are required to investigate long-term solutions and encourage behavioural changes [19]. Climate change communication methods must adapt in order to engage broad audiences and encourage real action [20]. Integrating climate change education into formal science curriculum allows students to build essential competences such as scientific literacy, systems thinking, and problem-solving skills [21].

Data is the essential foundation of research [22]. Bibliometric analysis is primarily reliant on the bibliometric data on certain variables, domains, subjects, authors, journals, or countries etc. It is critical and includes all relevant bibliometric information. Conducting bibliometric analysis using R-Biblioshiny and obtaining data from the Scopus database has been accorded academic prominence among higher education researchers [23], [24], [25], [26], [27], [28], [29], [30]. Climate change challenges have been addressed in a variety of sectors of our daily lives, including tourism [31], health hazards [32], fishers [33], railway [34], construction industry [35] etc.

Collaboration in academics and academic publication is crucial for growth and development since it helps authors, institutions, and countries as a whole in several ways [29]. Collaboration across authors, affiliations, and countries is critical in CCE research for a variety of significant reasons. Throughout the years, various initiatives and expenditures have been established to increase research capacity and encourage collaborative research [36]. Collaboration networks can be a beneficial supplement to publications and citation outputs [37], and academic contribution is acknowledged through citation [38], likewise collaboration and citation are essential in the realm of research and publications [39].

The Co-occurrence network analysis of authors' keywords provides useful insights into the academic landscape. The Co-occurrence network analysis of the author's keywords has been the top priority among scholars in bibliometric analysis in the academic landscape like [40], [41], [42], [43], [22], [44], [45].

Research Gap

Existing bibliometric studies highlight the climate change related aspects; bibliometrics on climate literacy [46], exploration of the international knowledge base on CCE [47], comprehensive analysis of the state of environmental education [48], understanding climate literacy research [49], trends in climate change education and experiential learning in science education [50], academic production on climate change in the educational field [51], bibliometric overview of climate literacy [52], overview of climate change and environmental risk [53] on climate change and related topics, have mostly focused on specific periods and frequently employed data from Scopus or Web of Science. However, there needs a research to look at a comprehensive longitudinal dataset containing the crucial combination of educational key terms 'climate change education' and 'climate literacy' as the combination that cover three decades from 1993 to 2024.

Research Questions

This study aims to evaluate the academic landscape of CCE research by addressing the following research questions:

1. What are the trends in annual publication growth, and which authors, journals, affiliations, countries, funding sponsors, and articles contribute most significantly to climate change education research?

2. How do collaborations occur among authors, affiliations, and countries within the field of climate change education?

3. What thematic clusters emerge from co-occurrence network analysis of authors' keywords, and what research trends can be identified from these clusters?

4. What future research agenda can be recommended for advancing research in climate change education?

METHODOLOGY

This study used bibliometric analysis, a systematic and quantitative approach which is exceptionally effective in investigating the changing landscape of CCE research. R Biblioshiny package was used, a software for science mapping, for bibliometric investigations that facilitates data analysis with advanced visualizations [54]. First, the Scopus database was searched, which is known for its comprehensive multidisciplinary coverage [22], using the following keywords: 'Climate Change Education, Climate Education, Climate Literacy, and Climate Change Literacy'. These keywords have been used as search words because they are closely related to the topic of education. After retrieving an initial dataset, a rigorous screening procedure was undertaken. Next, a systematic and rigorous inclusion and exclusion criteria used to further filter the dataset.

Exclusion and Inclusion Criteria

With the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) comprehensive literature search [55], Figure 1, was systematically conducted on 20th October 2024, in the Scopus

database of the scientific publications with scientific key terms "Climate Change Education" OR "Climate Education" OR "Climate Literacy" OR "Climate Change Literacy".

During the preliminary screening of literature, the authors found 5,257 documents using the search strategy ALL. Subsequently, the authors found 1,254 documents using the search strategy with TITLE-ABS-KEY. Further, the authors made a very precise search strategy and found 473 documents with TITLE.

Finally, the comprehensive inclusion strategy applied and found 321 documents with TITLE ("Climate Change Education" OR "Climate Education" OR "Climate Literacy" OR "Climate Change Literacy") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j")), inclusion of articles and reviews published in English language in journals. The final dataset of inclusion criteria of the articles (n=305) and reviews (n=16) that were published by journals in English language selected for further analysis. The reason behind the articles and reviews selection was to have the research based comprehensive overview.

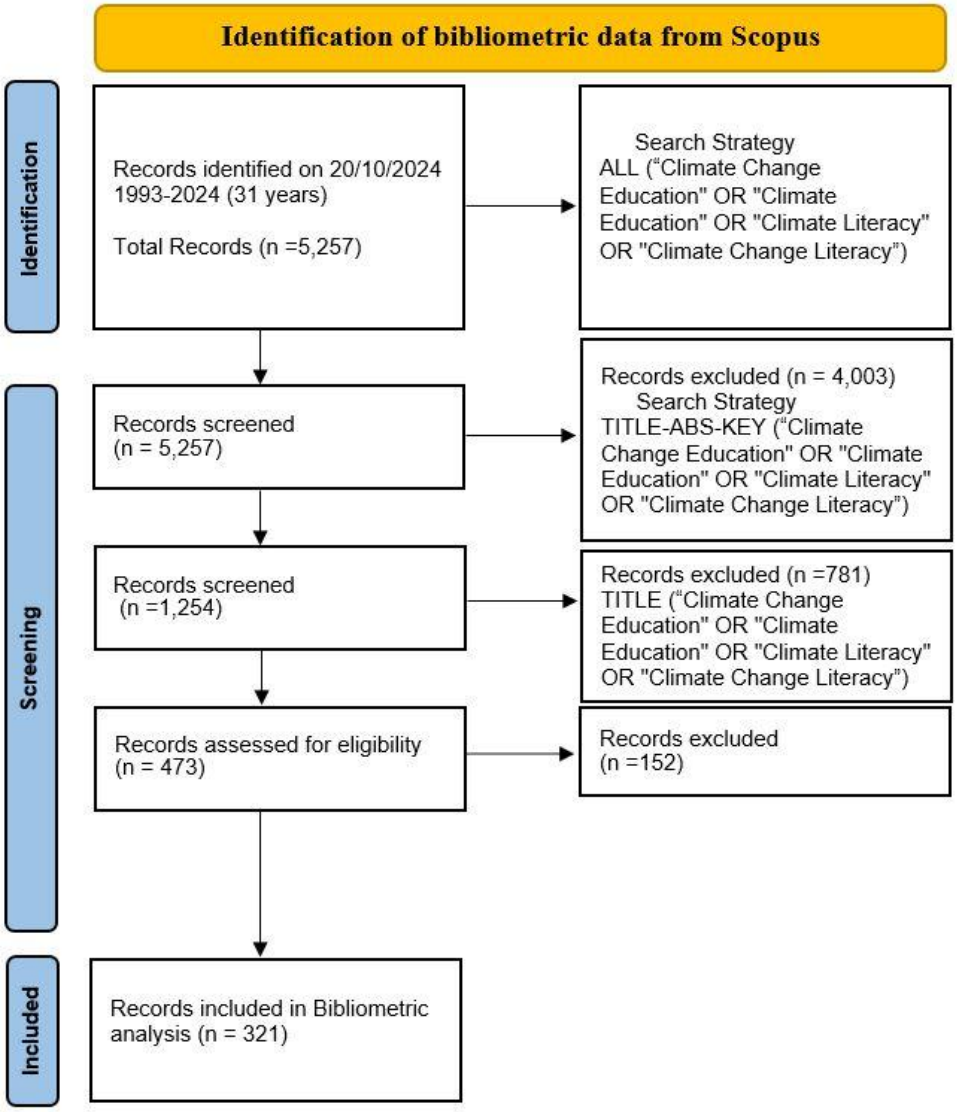

Figure 1: PRISMA-2020 flow diagram

RESULTS, FINDINGS AND DISCUSSION

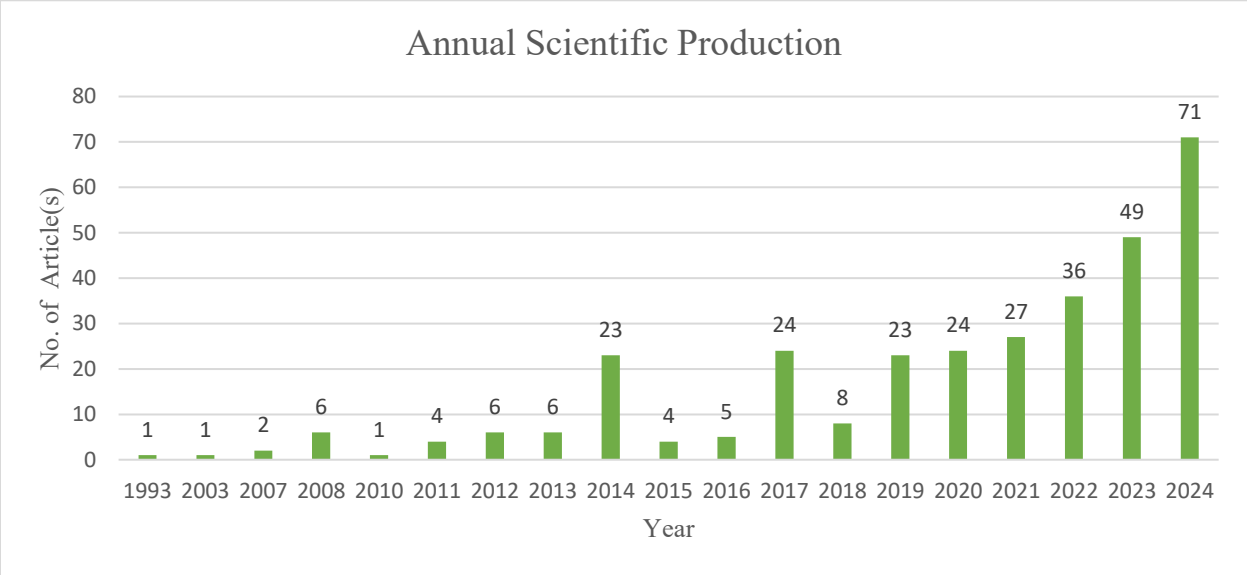

Figure 2: Annual Publication Productivity of CCE

The annual publication productivity, presented in Figure 2, reveals varied patterns in the expansion of CCE research between 1993 and 2024. Initially, articles appeared in the early era (1993-2007), with a notable decade-long hiatus until 2003. During the initial expansion period (2008-2013), there was a consistent presence, with 1 to 6 articles published. The first surge in 2014 displays tremendous growth, with 23 publications indicating CCE is getting increasingly often recognized. Sustained Growth Phase (2017-2024), increasing publications in 2024 reflect a considerable acceleration in scientific productivity, with 71 publications being the best level of publication productivity.

Table 1: Top Ten Cited Articles

Article's Title	Article Type	Access type	Authors	Journal's Name, Volume (Issue) and Page No.	Year of Publication	Scopus Citations
Identifying effective climate change education strategies: a systematic review of the research	Article (review)	Open Access	Monroe, M.C., Plate, R.R., Oxarart, A., Bowers, A., Chaves, W.A.	Environmental Education Research, 25(6), pp. 791–812	2019	529
A systematic review of climate change	Article (review)	Open Access	Rousell, D.,	Children's Geographies, 18(2), pp. 191–208	2020	244

education: giving children and young people a 'voice' and a 'hand' in redressing climate change			Cutter-Mackenzie-Knowles, A.			
Climate change education and the ecological footprint	Article	Open Access	Cordero, E.C., Todd, A.M., Abellera, D.	Bulletin of the American Meteorological Society, 89(6), pp. 865–872	2008	119
The role of climate change education on individual lifetime carbon emissions	Article	Open Access	Cordero, E.C., Centeno, D., Todd, A.M.	PLoS ONE , 15(2), 1-23	2020	114
The virtual field trip: Investigating how to optimize immersive virtual learning in climate change education	Article	Open Access	Petersen, G.B., Klingenberg, S., Mayer, R.E., Makransky, G.	British Journal of Educational Technology , 51(6), pp. 2098–2114	2020	109
What Is Climate Change Education?	Article	Closed Access	Stevenson, R.B., Nicholls, J., Whitehouse, H.	Curriculum Perspectives , 37(1), pp. 67–71	2017	109
GREENIFY: A Real-World Action Game for Climate Change Education	Article	Closed Access	Lee, J.J., Ceyhan, P., Jordan-Cooley, W., Sung, W.	Simulation and Gaming, 44(2-3), pp. 349–365	2013	96
Climate change education for universities: A conceptual framework from an international study	Article	Open Access	Molthan-Hill, P., Worsfold, N., Nagy, G.J., Leal Filho, W., Mifsud, M.	Journal of Cleaner Production , 226, pp. 1092–1101	2019	88
Clarifying climate confusion: Addressing systemic holes, cognitive gaps, and misconceptions through climate literacy	Article	Closed Access	McCaffrey, M.S., Buhr, S.M.	Physical Geography , 29(6), pp. 512–528	2008	85
Experimentation with a socio-constructivist process for climate change education	Article	Closed Access	Pruneau, D., Gravel, H., Bourque, W., Langis, J.	Environmental Education Research , 9(4), pp. 429–446	2003	83

Table 1 focuses on the top ten cited documents on CCE, revealing trends in academic production, publication types, access, and citation impact. A significant number of publications, six out of ten, are open access, indicating a research trend towards making research more available to the worldwide academic community. The publication time varies from 2003 to 2020, demonstrating a consistent scholarly interest in CCE over time. Interestingly, three publications published in 2020 have already been highly cited, with 244, 114, and 109 citations. The most cited article, '*Identifying effective climate change education strategies: a systematic review of the research*' (2019), has received 529 citations, demonstrating its rapid popularity in the field. The documents were published in a range of journals, with *Environmental Education Research* appearing twice, indicating its importance in the discussion over CCE. Other journals, such as *Children's Geographies*, *PLoS ONE*, and the *British Journal of Educational Technology*, are also represented, demonstrating that this area is related to geography, environmental sciences, and education technology. Additionally, multidisciplinary journals such as the *Journal of Cleaner Production* and *Bulletin of the American Meteorological Society* publish articles on CCE, demonstrating that it is researched not just within educational frameworks, but also in scientific and environmental contexts.

Cordero, E.C. is a prominent contributor, appearing twice on this top-cited list, indicating expertise and influence in the subject. Two of the top three most-cited articles are systematic reviews that highlight the success of education programs and include children's perspectives. The documents from 2019 to 2020 have received more citations. The possible reasons for high citation impact are; Open access publication, literature review documents and technology inclusion in CCE appear to have a considerable effect on citation impact, highlighting the necessity of accessibility in sharing vital educational research. The diverse emphasis on educational practices, student participation, and carbon footprint reduction underscores the multidisciplinary nature of this growing academic field.

Table 2: Top Ten Productive Journals

Journal Title	**Scopus Indexing period**	**Publisher**	**Scopus indexing subject area**	**Publications**	**Scopus CiteScore 2023**
Environmental Education Research	1995 to 2024	Taylor & Francis	Social Sciences	38	6.1
Sustainability Switzerland	2009 to 2024	MDPI	Social Sciences	26	6.8
Journal of Geoscience Education	1996 to 2024	Taylor & Francis	Social Sciences, Earth and Planetary Sciences	18	3.2
Bulletin of The American Meteorological Society	1972 to 2024	American Meteorological Society	Earth and Planetary Sciences	6	9.8
Climatic Change	1977 to 2024	Springer Nature	Earth and Planetary Sciences and Environmental Science	6	10.2
International Journal of Global Warming	2009 to 2024	Inderscience Publishers	Environmental Science and Earth and Planetary Sciences	6	1.8

International Research in Geographical and Environmental Education	1992 to 2024	Taylor & Francis	Social Sciences	6	5.2
Applied Environmental Education and Communication	2002 to 2024	Taylor & Francis	Social Sciences	5	2.3
Physical Geography	1975, 1980 to 2024	Taylor & Francis	Earth and Planetary Sciences and Environmental Science	5	3.6
Curriculum Perspectives	1980 to 1994, 1996 to 2003, 2006 to 2024	Springer Nature	Social Sciences	4	2.5

According to the number of articles published on CCE, Table 2 lists the top ten most productive journals. The Journal, *Environmental Education Research*, has the most published documents, with 38 articles. This journal focuses exclusively on educational research in CCE. *Sustainability Switzerland* has published 26 articles, highlighting its multidisciplinary approach. The CiteScore figures indicate the journals' academic importance in 2023, with *Climatic Change* (10.2) and *Bulletin of the American Meteorological Society* (9.8), *Sustainability Switzerland* (6.8), and *Environmental Education Research* (6.1) receiving the highest CiteScores. Among the journal publishers, *Taylor & Francis* leads the academic publications of CCE, publishing five of the top ten among the most productive publishers. This shows that *Taylor & Francis* is highly engaged, followed by other leading publishers. Scopus indexing periods reveal information on the longevity and academic evolution of these journals.

Table 3: Top Ten Productive Authors

Author's Name	**Publications**	**Affiliation and Country**	**Total no. of documents in Scopus with their Citations by no. of Documents Cited**	**Author's h-index**
Lars Keller	11	Universität Innsbruck, Austria	33 Documents, 324 Citations by 263 documents	11
Johann Stötter	6	Universität Innsbruck, Austria	91 Documents, 2,181 Citations by 1,842 documents	27
Veronika Deisenrieder	4	Universität Innsbruck, Austria	7 Documents, 63 Citations by 57 documents	4
Efrat Eilam	4	Victoria University, India	19 Documents, 350 Citations by 333 documents	10
Melanie Frick	4	Universität Innsbruck, Austria	6 Documents, 23 Citations by 21 documents	3
Nina Liebhaber	4	Universität Innsbruck, Austria	6 Documents, 23 Citations by 21 documents	3

Edward W. Maibach	4	George Mason University, The United States	236 Documents, 16,329 Citations by 12,188 documents	69
Martha C Monroe	4	University of Florida, The United States	122 Documents, 3,285 Citations by 2,840 documents	25
Essi Aarnio-Linnanvuori	3	Tampere University, Finland	7 Documents, 110 Citations by 108 documents	2
Diego Corrochano	3	Universidad de Salamanca, Spain	31 Documents, 212 Citations by 199 documents	7

Table 3 shows the research output and impact of the most productive authors in CCE publications. *Lars Keller* of Universität Innsbruck, Austria, is the most productive author in CCE research, with 11 publications and an h-index of 11. However, his modest h-index suggests a specialized yet influential presence in the area, implying that his contributions are notable within a broader academic audience focused on environmental education and policy. *Johann Stötter*, the second most productive author from the same institute, with 6 publications and an h-index of 27, demonstrates a high h-index reflects his larger academic effect, notably in allied fields like sustainable development, which reinforces CCE. On the other hand, authors like *Martha C. Monroe* with 4 publications, h-index 25), from the University of Florida, USA, and *Edward W. Maibach* with 4 publications, h-index 69, from George Mason University, USA, show the impact of authors whose research goes far beyond the boundaries of CCE but still significantly shapes the field. More specifically, *Edward W. Maibach* is an example of an author whose larger contributions to climate change policy and communication have a significant impact on CCE with h-index 69.

The strong multidisciplinary focus of CCE researchers is further demonstrated by *Veronika Deisenrieder* with 4 publications, h-index 4, who specializes in interdisciplinary and trans-disciplinary methods. Similarly, *Efrat Eilam* with 4 publications, h-index 10, of Victoria University from India provides a new interdisciplinary perspective by bringing mindfulness and scientific education into the CCE discourse. *Diego Corrochano*'s 3 publications, h-index 7, from the Universidad de Salamanca in Spain exemplify this interdisciplinary by including Earth sciences, geography education, and nutrition education, demonstrating how CCE is linked across many disciplines.

Geographically, CCE research is being conducted in a variety of areas, including contributions from experts in Europe, the United States, and beyond. The significant presence of researchers from Universität Innsbruck, Austria, such as *Lars Keller*, *Johann Stötter*, *Melanie Frick*, and *Nina Liebhaber*, demonstrates the institution's significance as a hub for CCE and environmental policy research across Europe. In contrast, *Edward W. Maibach* and *Martha C. Monroe* are major voices from the United States who have contributed to the global conversation on CCE via their important work in climate change communication, policy, and environmental education. At the same time, *Essi Aarnio-Linnanvuori*, with 3 publications, h-index 2, from Tampere University in Finland provides a new perspective on the relationship between environmental policy and education for sustainable development learning.

Table 4: Top Ten Productive Affiliations

Affiliation's Name	**Publications**	**Affiliation's country**
Universität Innsbruck	11	Austria
Pennsylvania State University	6	The United States
NC State University	6	The United States
Cooperative Institute for Research in Environmental Sciences	6	The United States

University of Florida	6	The United States
George Mason University	6	The United States
University of Nebraska–Lincoln	6	The United States
University of Wisconsin-Madison	6	The United States
University of Colorado Boulder	5	The United States
National Institute of Education	5	Singapore

The institutions listed in table 4 made a significant contributions to CCE research, demonstrating their leadership in impacting worldwide discourse around CCE. *The United States*, which leads this ranking with eight universities providing six or more articles each, is home to the majority of the top ten institutions. This demonstrates how important the US is to the advancement of CCE research. Leading affiliations from The US include the *University of Florida*, *George Mason University*, *Pennsylvania State University*, and *NC State University*. Outside of the United States, *Universität Innsbruck* in Austria and the *National Institute of Education* in Singapore make significant contributions, reflecting European and Asian research efforts in CCE. *Universität Innsbruck* leads the ranking with 11 publications, making it the most active university in this field. Its considerable output shows that Austria is a key player in CCE research in Europe. Universities such as *Pennsylvania State University* and the *University of Nebraska-Lincoln* have established themselves as major contributors to the area, through numerous publications. The existence of the *Cooperative Institute for Research in Environmental Sciences* and the *University of Colorado Boulder* highlights the multidisciplinary pattern of CCE in the United States, where education intersects with environmental sciences, policy, and sustainability.

Table 5: Top Ten Productive Countries

Country's Name	**Publications**
The United States	121
The United Kingdom	42
Australia	28
Germany	21
Canada	16
Austria	14
South Africa	10
Finland	9
Portugal	9
The Netherlands	8

Table 5 reveals the top ten most productive countries in CCE, emphasizing worldwide engagement and academic dominance. Several factors contribute to the differences in publication output across these countries, including government policies, educational systems, climate change programs, and research funding. *The United States* leads the way with 121 research publications with strong financing systems. *The United Kingdom* comes second with 42 publications, with the European Union and Commonwealth. *Australia* has 28 publications, placing it third. Given *Australia's* direct susceptibility to climate change and its regular occurrence of extreme weather events like floods, droughts, and wildfires, climate education should be a top concern for the country. *Germany* has 21 publications, placing it fourth with major targets for carbon reduction and renewable energy. With 16 publications, *Canada* comes in fifth place, mostly because of its abundance of natural resources and proximity to climate-related problems like forest degradation and ice cap melting, which makes climate education essential to the country's sustainability strategy. Among the top country publications, other countries like *Austria* with 14, *South Africa* with 10 followed by *Finland* with 9, *Portugal* with 9 and *The Netherlands* with 8 publications.

Table 6: Top Ten Funding Sponsors

Funding Sponsor	Publications	Country	Funding Sponsor's Affiliation
National Science Foundation	22	The United States	Independent Federal Agency
European Commission (Erasmus+)	6	Belgium (Brussels)	Governmental Organization
Deutsche Forschungsgemeinschaft	5	Germany	Governmental Organization
National Institute of Food and Agriculture	5	The United States	Governmental Organizations
Directorate for Education and Human Resources	3	The United States	Governmental Organization
Engineering and Physical Sciences Research Council	3	The United Kingdom	Governmental Organization
National Aeronautics and Space Administration	3	The United States	Governmental Organization
UK Research and Innovation	3	The United Kingdom	Governmental Organization
China Scholarship Council	2	China	Governmental Organization
Department of the Environment, Climate and Communications	2	Ireland	Governmental Organization

Table 6 of the major funding sources in CCE research displays many interesting patterns of geographical distribution and funding concentration. Analyzing the primary financial organization indicates that the *National Science Foundation (NSF)* is the leading funding sponsor, sponsoring 22 publications, a much larger share than other funding agencies in CCE research. The geographical distribution of financial sponsors exhibits a distinct concentration in Western nations. The global distribution of funding sponsors reveals an evident concentration in Western countries, with the United States leading with multiple major funding bodies such as the *National Science Foundation* (22 articles), *National Institute of Food and Agriculture* (5 articles), *Directorate for Education and Human Resources* (3 articles), and *National Aeronautics and Space Administration* (3 articles). The European representation is recognized through the *European Commission's Erasmus+* program (6 articles), Germany's *Deutsche Forschungsgemeinschaft* (5 articles), and UK-based organizations such as the *Engineering and Physical Sciences Research Council* (3 articles) and *UK Research and Innovation* (3 articles). Asia is predominantly represented by the *China Scholarship Council* (2 articles). The dominance of governmental organizations in the funding environment is notable. This governmental dominance implies that CCE research is predominantly funded by the public sector, rather than private or corporate support. This stratification shows that funding sources should be diversified to provide long-term and balanced research support for CCE.

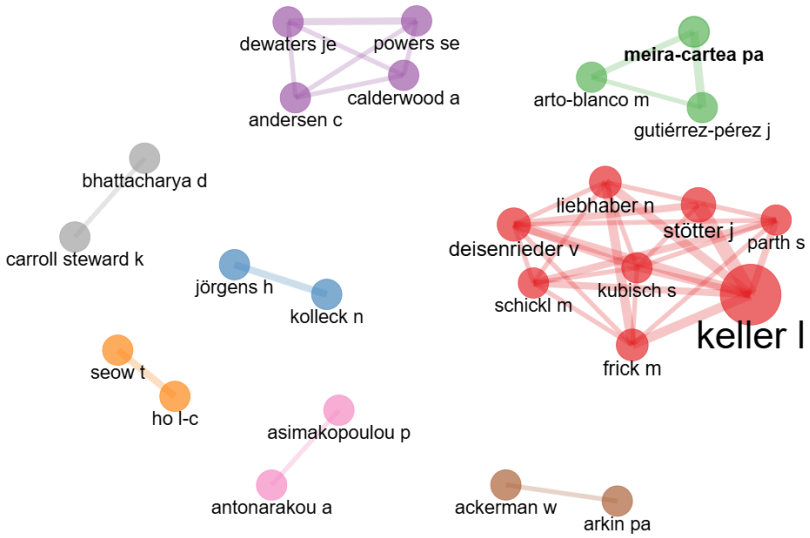

Figure 3: Authors' Social Network

Figure 3 depicts multiple distinctive author collaboration networks in CCE research, identified by different colours and node sizes that signify the strength of collaboration and author impact in the area. Cluster Distribution shows the authors are divided into eight separate clusters, demonstrating that well-defined groups of researchers collaborate across specific subfields of CCE. The largest Red cluster, centred on *Keller l*, indicates that this researcher is a key influential author in CCE. This cluster is strongly interconnected with multiple collaborators, including *kubisch s*, *deisenrieder v*, *liebhaber n*, *stötter j*, *parth s*, *schickl m*, and *frick m*. The dense connections among these authors point to a well-established research group with significant academic output. The Purple Cluster, which consists of *Dewaters je*, *powers se*, *Calderwood a*, and *Andersen c*, demonstrates modest collaborative relationships. The Green Cluster, including *Meira-cartea pa*, *Arto-blanco m*, and *Gutiérrez-pérez j*, may signify a regional or institutional collaborative group, followed by the Blue Cluster which demonstrates direct cooperation between *jörgens h* and *Kolleck n*. The pairs of smaller collaborative clusters reveal the Grey cluster with *Bhattacharya d* and *Carroll steward k*; the Orange cluster has Seow T and *ho l-c*; the Pink cluster has *Asimakopoulou p* and *Antonarakou a*; and the Brown cluster has *Ackerman w* and *Arkin pa*.

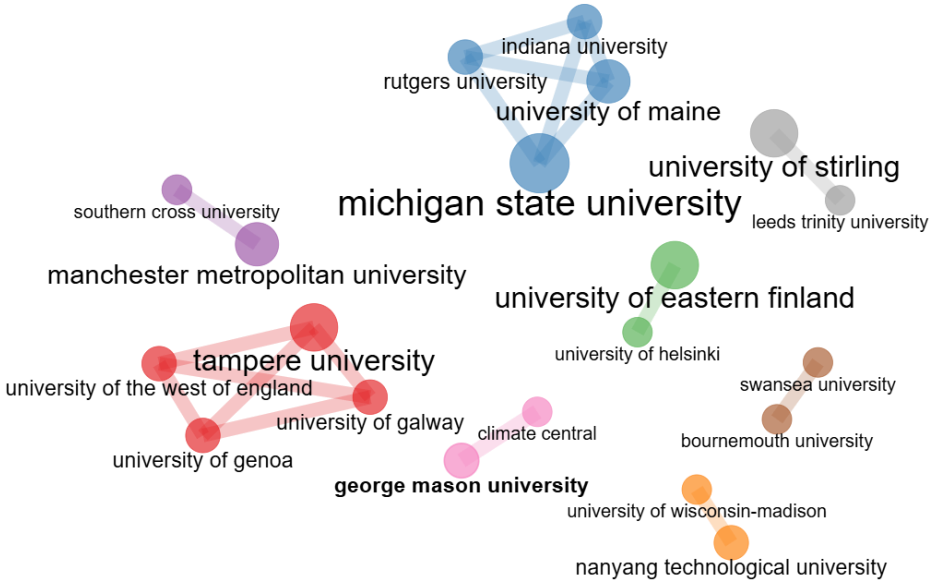

Figure 4: Affiliations' Social Network

Figure 4 displays a network visualization of eight unique institutional collaboration clusters in CCE research. The Blue Cluster depicts U.S. universities centred on *Michigan State University*, including *Indiana University*, *Rutgers University*, and the *University of Maine*. *Michigan State University* is the biggest node, suggesting institutional leadership and a key role in CCE research. This cluster exemplifies major inter-state collaboration in US higher education. The red cluster depicts a European-Finnish cluster centred on *Tampere University*, notable collaborations with the *Universities of the West of England*, *the University of Galway*, and the *University of Genoa* reveal substantial trans-European institutional collaboration. The Green Cluster represents Finnish institutions. *The University of Eastern Finland* and the *University of Helsinki* demonstrate substantial national-level collaboration in Finnish CCE research. The grey cluster depicts the UK Institutional Pairs, including the *University of Stirling* and *Leeds Trinity University*. *Swansea* and *Bournemouth* universities are shown by the brown cluster. The purple cluster indicates an Australian-UK connection with *Southern Cross University* and *Manchester Metropolitan University*. The orange cluster represents the Asian-American connection to *Nanyang Technological University* and the *University of Wisconsin-Madison*. The pink cluster represents the partnership between *George Mason University* and *Climate Central*.

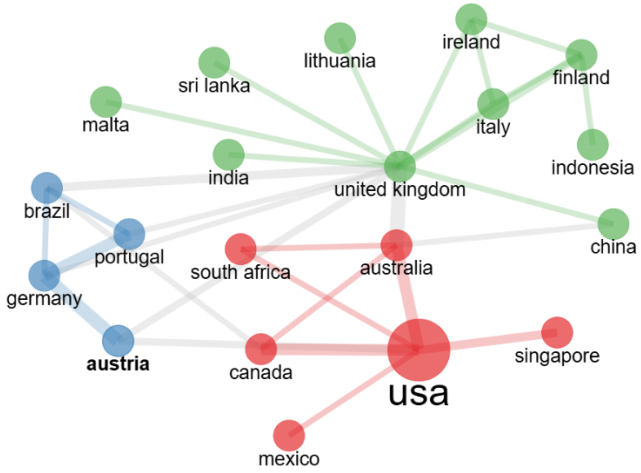

Figure 5: Countries' Social Network

The Country Collaboration Network, visualization in Figure 5, identifies three major collaborative clusters and depicts the international research environment in CCE. The Larger node sizes indicate increased research output or collaboration intensity. The primary cluster, depicted in red, shows *the United States* as the major research centre with the highest node size, demonstrating its prominent position in CCE research. Strong bilateral cooperation with *Canada* and *Australia* indicates significant ties, while *Singapore* and *Mexico* show direct interconnections, and South Africa represents North-South engagement. The blue cluster represents European collaboration. *Germany*, *Portugal*, *Austria*, and *Brazil* have considerable intra-European collaboration, with *Brazil*'s involvement suggesting transatlantic research partnerships. *Austria* appears to function as a bridge between this cluster and other networks. The UK-Centered Network in Green Cluster indicates that *the United Kingdom* serves as a secondary hub with numerous peripheral connections to various geographical regions, including European nations such as *Ireland*, *Italy*, *Finland*, *and Lithuania*, Asian countries such as *Indonesia*, *China*, *Sri Lanka*, a small island state as *Malta*, and a South Asian region as *India*. Since climate change is an international priority, developing collaborations among premier institutions in the United States, Europe, and Asia might result in novel, scalable educational frameworks that address climate literacy on an international level. The presence of both developed and developing countries suggests diversified viewpoints. Collaboration patterns include geographic clustering particularly in North America and Finland, cross-continental collaboration, and combination of public and private institutions, limited inter-cluster connection, and strong intra-regional collaboration.

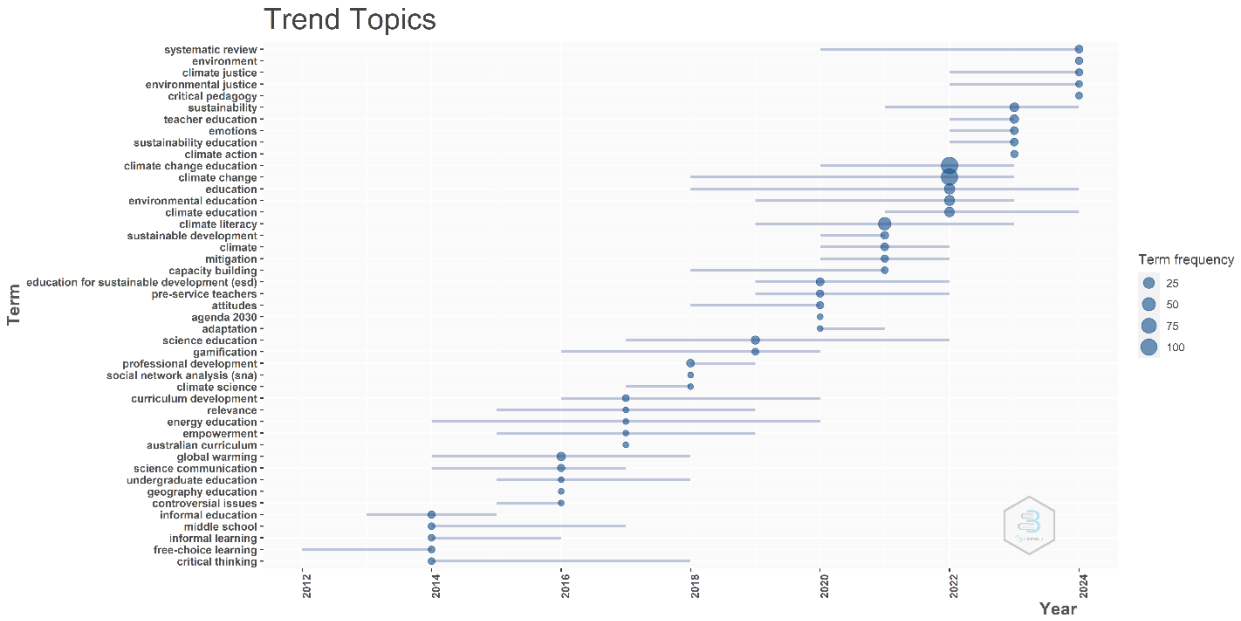

Figure 6: Trending Topics in Climate Change Education

Figure 6 reveals the trend analysis of the author's keywords in CCE during the latest decade, from 2012 to 2024. The keywords are categorized according to their frequency as well as prominence in articles published during the period. There is a rising focus and attention on key concepts such as 'climate change education, sustainability education, climate justice, and environmental education' from 2018 to 2024, with word frequency peaking between 2020 and 2024. These advancements indicate a developing multidisciplinary approach to addressing climate change via education, emphasizing not only scientific but also socio-environmental and justice-related factors. The emerging concepts such as 'climate literacy, climate action, and environmental justice' are becoming more popular beginning in 2020. These phrases represent a growing understanding of the need for practical knowledge and justice frameworks in educational settings, which is consistent with global climate action initiatives e.g., the Paris Agreement (COP21) and the SDGs. The foundational themes of 'education for sustainable development (ESD), sustainable development, and teacher education' stay continuous throughout the decade, serving as a foundation for new topics to arise. Terms such as 'critical pedagogy, gamification, and professional development' have been more prevalent in recent years, indicating a pedagogical advancement. The specific educational contexts such as 'middle school, pre-service teachers, and informal learning' highlight a growing diversity in educational settings. This underscores the trend towards incorporating climate education into both formal and informal educational environments. Terms like 'Agenda 2030 and adaptation' indicate that educational research is aligned with global sustainability frameworks and policies, such as those established by the United Nations. The trend analysis reveals a dynamic emerging field, with a greater emphasis on justice, action, and innovative pedagogy. The ongoing integration of sustainability and development goals, together with evidence-based research approaches, demonstrates the evolving nature of CCE research as it responds to global challenges and educational needs.

Figure 7: Word Cloud of Top 100 keywords in Climate Change Education

Figure 7, depicts the word cloud of the top 100 most prominent keywords used by authors in the field of CCE. The size of each word correlates to its frequency. This word cloud uncovers dominating themes and emerging fields of interest in CCE research. The largest keywords, such as 'climate change, climate literacy, environmental education, and sustainability,' represent essential topics that are key to CCE such as knowledge, comprehension, and education about climate challenges. Keywords such as 'education for sustainable development (ESD) and climate change education (CCE)' indicate climate education's integration into greater sustainability targets, as well as the emphasis on integrating such topics into the educational curriculum.

Significant key terms, such as 'curriculum, policy, teacher education, and higher education,' reveal a major emphasis on designing and implementing climate change issues at all levels of education, as well as informing educators to teach these areas successfully. The key terms 'attitudes, emotions, and engagement' emphasize the psychological and behavioural aspects of climate education, indicating a focus on how education may foster environmental values and drive pro-environmental behaviours. The inclusion of 'social norms, justice, equity, and empowerment' demonstrates a rising understanding of social factors, such as environmental justice and equitable climate solutions, which are getting more prominent in climate education discourse.

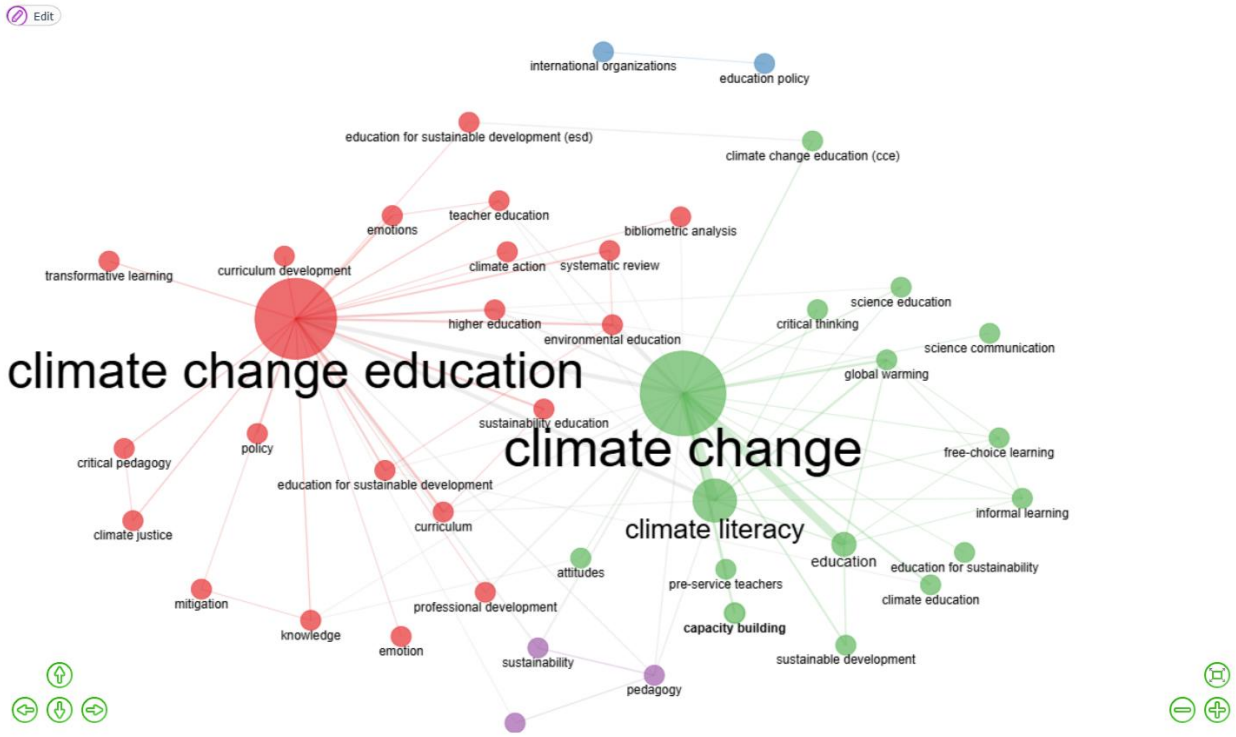

Figure 8: Co-occurrence Network of Author's Keyword

The author's keyword co-occurrence network in Figure 8 reveals a complicated network with primary thematic clusters. The Red Cluster 'Climate change education' appears as a main node, demonstrating its importance in the field and strong links to pedagogical features such as curriculum development, transformative learning, teacher education, critical pedagogy, and professional development. The educational policy themes include ESD, higher education, and policy. The emotional and social components cover emotions, climate justice, and climate action. The green cluster 'Climate Change' is the second main hub, focusing on educational approaches such as science education, communication, critical thinking, free-choice learning, and informal learning. Climate literacy, capacity building, sustainability education, and sustainable development are all examples of practical implementation components. The supporting themes in blue and purple represent the international and policy context, including international organizations and education policy. The pedagogical foundations cover pedagogy, sustainability, and environmental education. The author's keyword co-occurrence network shows strong connections between educational and climate science topics, including theoretical and practical keyword linkages.

IMPLICATIONS

The findings have significant implications for policy and practice in CCE. First, the prevalence of government financing implies a strong public commitment to climate literacy, however diversifying funding sources may improve research sustainability. Increased private-sector and philanthropic financing would ensure the long-term financial stability of CCE research, allowing for initiatives that promote cross-sectorial and community-based methods. The study emphasis on collaborative, multi-author research underscores the need of collaboration across disciplines and countries, particularly given the global interconnectedness of climate change implications. Institutional collaboration between the Global North and South are already obvious, but they should be extended further to include varied educational frameworks and settings. South-South alliances, might provide useful

insights from places that are more vulnerable to climate change, and also increasing the inclusion and relevance of CCE research and educational initiatives.

FUTURE RESEARCH AGENDA

In recent years, the rising urgency of climate change has created an extraordinary demand for CCE that transcends traditional educational boundaries, emphasizing collaborative, emotional, community-based, and technologically connected techniques. Based on the results and findings the following is the research agenda proposed for the future in Figure 9.

Figure 9: Research Agenda

Enhanced South-South Collaboration: Collaborating with developing countries would generate various perspectives, particularly from regions significantly affected by climate change. These collaborations might concentrate on localized, culturally relevant climate education strategies that address specific geographical challenges.

Integration of Emotional and Psychological Components: The publication trends highlight the importance of emotional and psychological components in climate literacy. Future study could enquire into frameworks that combine empathy, resilience, and personal responsibility to provide a comprehensive approach to CCE.

Focus on Informal and Community-Based Education: Besides formal education, informal community initiatives are critical to improving climate change awareness. Researchers should look at how community-based and experiential learning could raise climate change awareness, particularly among people with limited access to formal educational resources.

Policy Recommendations for Inclusive funding: Given the largely public financing framework, governments should explore private investment in CCE. Expanding sources of funding would help balance research priorities, allowing for a broader range of initiatives that address local, national, and worldwide CCE agendas.

Technological Integration for Broader Accessibility: The significance of technology in making CCE more accessible. Future research might design and test accessible digital platforms that democratize access to CCE resources, particularly for under-represented populations and areas with insufficient educational infrastructure.

This research agenda seeks long-term, collaborative, and inclusive initiatives to promote CCE, tackling the complex challenges faced by the global climate catastrophe in an innovative and accessible manner.

CONCLUSION

The bibliometric analysis of Climate Change Education (CCE) sheds significant light on the field's rapidly growing scope and multidimensionality. The significant rise in publications, particularly in the last five years, reflects an increased worldwide awareness and financing for CCE research in response to pressing climate issues at the international level. The present research study findings highlight the interdisciplinary approach of CCE, which incorporates environmental, technical, psychological, and societal components to create a comprehensive framework for addressing climate change, climate literacy and climate change education as predominant variables. Overall, this study presents a road map for expanding the horizon of CCE as a key component of global education, emphasizing the significance of collaborative, inclusive, and accessible ways to prepare policy frameworks for the current and future generations for the challenging realities of climate change and education.

DECLARATION OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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