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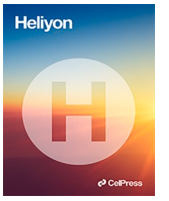

Review article

Understanding climate literacy research using scientometrics analysis

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ABSTRACT

Climate literacy, critical for understanding both the individual's impact on climate and the consequential effects on society and the biosphere, is comprehensively examined in this study through scientometric analysis. Spanning research from 1981 to 2024 and utilizing the Web of Science database, this study maps the evolution of publication trends, pinpoints central themes, and identifies pivotal publications within the domain. Leveraging advanced visualization tools like CiteSpace, the research employs dual-map overlays and document co-citation analysis to uncover the intricate web of interconnections among scholarly works. Findings highlight a significant surge in publications after 2015, mirroring the escalating global consciousness of climate-related issues. Predominant research clusters identified include "bad news," "mental health," and "farmers' perceptions," showcasing the field's thematic diversity. These insights emphasize the indispensable role of interdisciplinary methods in advancing public knowledge and active participation in climate change mitigation and adaptation efforts, fostering a well-informed community poised to address environmental challenges.

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1. Introduction

The escalating crisis of global carbon dioxide emissions, reaching an unprecedented high of 37.15 gigatonnes in 2022, underscores the critical need for immediate action to combat climate change [1,2]. This significant rise is largely attributed to the power and heat generation sectors, which experienced a 1.8 % increase in emissions searching 14.6 Gt CO_2 within the same timeframe [3]. To address these challenges, enhancing public awareness of the impacts of climate change and the necessary countermeasures is imperative. Article 6 of the United Nations Framework Convention on Climate Change (UNFCCC) highlights the importance of education and public awareness programs, access to information, and public understanding of climate change implications [4]. It is essential to correct misconceptions influenced by mass media and clarify scientific debates to foster an informed public perception [5,6].

Achieving carbon neutrality is vital but faces challenges due to gaps in stakeholder knowledge and attitudes toward energy efficiency and renewable energy. Despite extensive discussions, the specific deficits in understanding and attitudes that impede the effective adoption of these initiatives are often overlooked. There is a noticeable disconnect between climate literacy and the practical comprehension of scientific terms, which contributes to general indifference towards policy interventions. This indifference is further compounded by the rising interdisciplinary issues associated with climate change, underscoring the urgent need for effective climate literacy interventions. Furthermore, the persistence of climate change denial continues to undermine educational efforts, making it imperative to confront misinformation through targeted literacy and social studies programs [7,8].

Past studies on climate literacy have shown mixed outcomes, often hindered by socio-economic challenges and infrastructural limitations. Research by Refs. [9–11] indicates that while discussions on these topics are extensive, a deep understanding and positive attitudes necessary for successful implementation are frequently absent. This gap is particularly evident in detailed examinations, as noted by Ref. [12]. Moreover, environmental education is critical for enhancing awareness and understanding of global warming, which is essential for preparing students for impactful societal roles.

Despite numerous studies highlighting the importance of climate literacy [11,12], it is crucial to recognize that these literature reviews, while providing valuable insights, also have inherent limitations. These reviews often focus narrowly on specific issues or disciplines, a constraint arising from the labor-intensive process of sifting through a substantial volume of publications, identifying key concepts, and drawing meaningful conclusions. To overcome this limitation and obtain a broader perspective, scientometrics, a

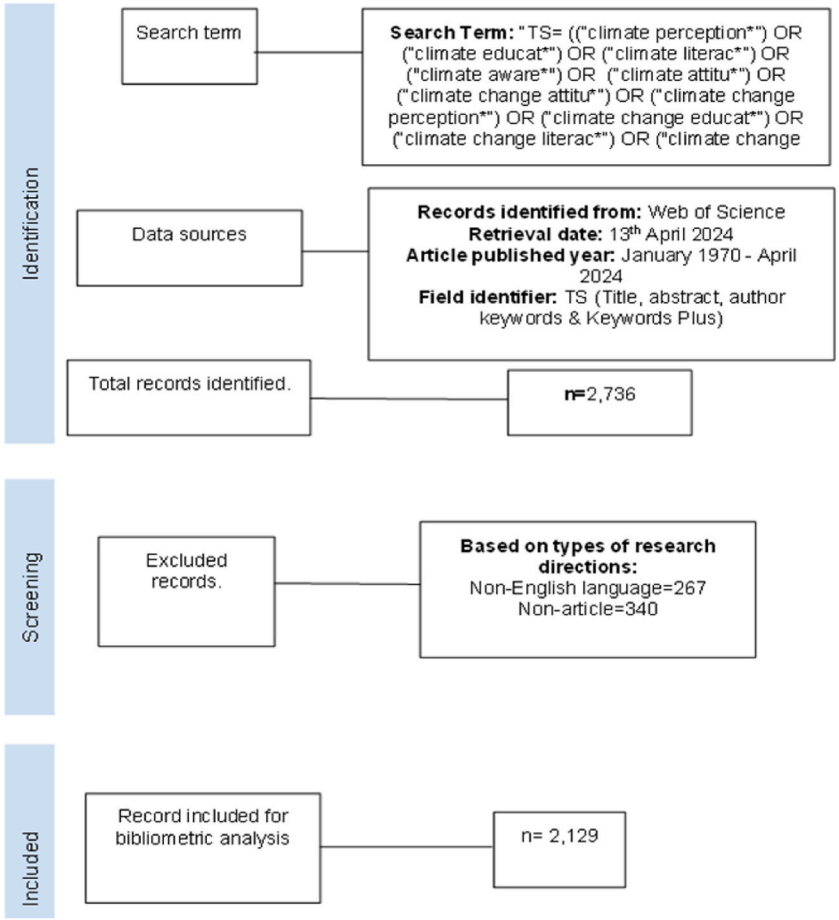

Fig. 1. Methodological framework for the current study.

quantitative method for assessing scientific performance, is employed. This approach, utilized in various research areas such as marine science, health, and renewable energy studies [12–14], includes a range of quantitative techniques from basic descriptive statistics and data visualization to advanced method like network analysis, machine learning algorithms, mathematical analysis, and computer simulation. This study aims to synthesize climate literacy research published between 1981 and 2024 using the Web of Science database and the scientometrics tool, CiteSpace. This research seeks to answer three key questions: (i) What are the overall publication trends in terms of output? (ii) What are the central topics/clusters? and (iii) What are the most influential publications in these domains? A comprehensive discussion of these findings will be elaborated upon in the subsequent sections.

2. Methodology

This study utilized the scientometrics approach to examine scholarly articles on Climate Literacy indexed in the Web of Science (WoS) database from 1981 to 2024 [12,13].

2.1. Database searches

Data were systematically extracted from the WoS Core collection database provided by Clarivate Analytics, renowned for its comprehensive repository of scholarly information (Fig. 1). This database is pivotal in various research domains, especially scientometrics, due to its broad scope covering multiple disciplines. It is acclaimed for its robust capabilities in ranking countries, journals, scientists, papers, and institutions across diverse scientific fields. The database includes over 6650 prominent journals across 150 scientific disciplines and features all cited references from indexed articles [12,13].

A structured keyword search was conducted in WoS, employing a wildcard "*" to capture various derivations of the search terms. The database was queried using the following search string in the “TS” field, covering manuscript titles, abstracts, keywords, author names, and Keywords Plus: TS= ((“climate perception*”) OR (“climate educat*”) OR (“climate literac*”) OR ("climate aware*") OR (“climate attitu*”) OR (“climate change attitu*”) OR (“climate change perception*”) OR (“climate change educat*”) OR (“climate change literac*”) OR ("climate change aware*") OR (“climate change knowledge”) OR (“pro$climate behavior”)).

The search was limited to original research articles published between 1981 and 2024, excluding other document types like commentaries, books, and editorials to focus on primary research. The search was executed on April 13, 2024.

2.2. Data analysis

Data analysis was segmented into two categories: Descriptive Analysis and Scientometrics Analysis.

2.3. Descriptive analysis

This analysis included evaluating the annual number of publications, identifying the journals, universities, and countries associated with the research. It provided an overview of the geographical distribution and institutional affiliations contributing to the field.

2.4. Scientometrics Analysis

CiteSpace 6.2 for Windows was employed for visualization and knowledge graph analysis. This tool facilitated the construction of bibliometric networks and enabled Dual-Map Overlay Analysis: This analysis categorized the literature into two groups: cited journals and citing journals, illustrating the relationship between them through a visual representation on a global map. The sizes of the ovals on the map represented the publication volume and citation counts, while the line thickness indicated the citation frequency between disciplines.

Additionally, document Co-Citation Analysis (DCA) identified instances where two sources were simultaneously cited in a single paper. The analysis provided metrics such as burstness (indicating spikes in citations), centrality (identifying influential articles within the network), and sigma (combining centrality and burstness to gauge the novelty and impact of research). Articles with centrality values exceeding 1 were considered pivotal, serving as connectors within the network. Sigma combines centrality and burstness to identify nodes that are both central in the network and experiencing a significant surge in attention, highlighting their overall impact and novelty. These characteristics are quantified using specific formulas, that mathematically represent the underlying principles that make centrality, burstness, and sigma effective indicators in DCA.

2.5. Centrality

CB(v) =

$$C_B(v) = \sum_{s \neq v \neq t} \frac{\sigma(s,t|v)}{\sigma(s,t)}$$

- **CB(v) C_B(v)** = Betweenness centrality of node v

- **σ(s,t)**: Total number of shortest paths from node s to node t
- **σ(s,t|v)**: Number of shortest paths from s to t that pass through node v

This formula measures the extent to which a node v lies on paths between other nodes, indicating its importance in the network.

2.6. Burstness

$$F_i(t) = \lambda^{(t-t_i)} e^{-\lambda t_i} \prod_{i=1}^{k} \left(\frac{\gamma_i}{1-\gamma_i} \right)^{x_i}$$

- **$F_i(t)$**: Burst function for event i at time t
- **λ**: Base rate of events
- **t_i**: Time of event i
- **γ_i**: Probability of event i being in a burst state
- **x_i**: Number of occurrences of event i in the burst state

This formula models the probability of an event experiencing a sudden burst in frequency, based on the deviation from a baseline occurrence rate.

2.7. Sigma

$$\sigma = (C+1) \times log_{10}(B+1)$$

- **σ**: Sigma metric, indicating the novelty and influence of a node
- **C**: Betweenness centrality of the node
- **B**: Burstness strength of the node

Clusters in the DCA were identified using the Log-Likelihood Ratio (LLR), ensuring optimal cluster uniqueness and coverage. The network's structure was visualized through timeline and cluster views, aiding in the understanding of the research domain's evolution and interconnections. The quality and coherence of the clusters were assessed using the Modularity Q index and the Silhouette metric, which measure the reliability and homogeneity of the clusters, respectively. This methodology provides a robust framework for comprehensively understanding the dynamics and impact of research within the field of climate literacy.

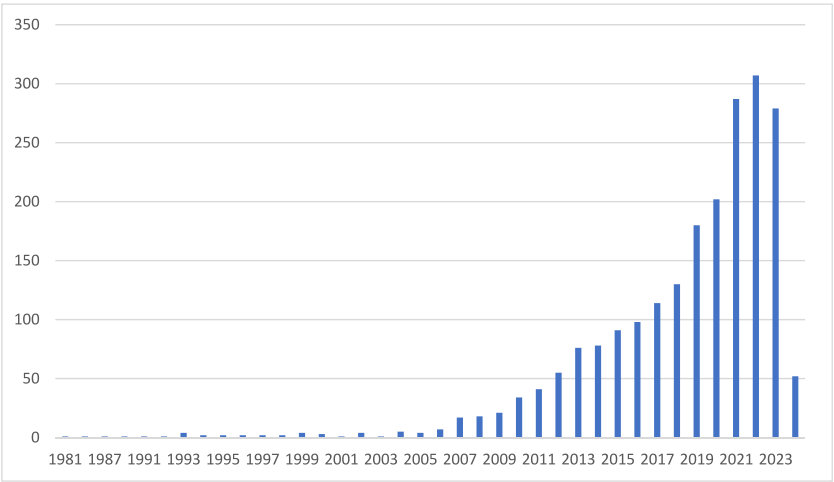

Fig. 2. Number of research articles regarding Climate Literacy published annually since 1981.

3. Result

3.1. Descriptive result

3.1.1. Evolution of published studies

In total, our search, as outlined in the methodology section, retrieved 2129 publications that boast an h-index of 94. These publications have been cited 47,328 times, resulting in an average citation rate of 22.23 citations per article. Fig. 2 illustrates the trajectory of climate literacy research spanning from 1981 to 2024. The data indicate that the field experienced a gradual increase in scholarly attention from 1981 until the early 2000s, with only a modest number of publications each year. This period reflects the nascent stage of climate literacy as a research area. From the mid-2000s, there was a marked increase in publications, suggesting a burgeoning interest in the field. The number of publications spiked dramatically from around 2015 onwards, indicating a surge in research that could be associated with a broader acknowledgment of climate change issues and their criticality.

Fig. 3 provides an overview of the countries actively contributing to research in the field of climate literacy. The intensity of the color in each country corresponds to the number of research records from that location, with a scale on the side indicating the range from a minimum of 1 to a maximum of 776 records. Countries with darker shades represent higher research output in climate literacy, while lighter shades represent lower output. The counts vary widely, with the United States leading by a substantial margin with 776 publications, followed by other countries like the United Kingdom, Australia, and the People's Republic of China with 225, 186, and 141 records, respectively. Most other countries have much lower counts, many in the single digits, indicating a wide disparity in research output on climate literacy. This could reflect the differences in research capacity, funding availability, academic infrastructure, and the prioritization of climate change issues among countries.

The top ten journals with the highest number of publications related to climate literacy, along with the count of articles and their corresponding percentages of the total 2129 records collected is presented in Table 1. "Sustainability" leads with 117 publications, constituting approximately 5.496 % of the total. It is followed by "Environmental Education Research" with 62 records (2.912 %) and "Climatic Change" with 57 records (2.677 %). The rest have lower counts, ranging from 29 to 19 publications. The percentages indicate each journal's share of the total body of literature in the dataset, providing a sense of where the majority of climate literacy research is published.

3.2. Scientometrics

Scientometrics analysis was conducted to illuminate the intellectual terrain of climate literacy research, encompassing publications from 1981 to 2024. This comprehensive analysis involved a dual-map overlay and document co-citation analysis (DCA) to trace the development of this specialized research domain over time. The entire climate literacy research domain comprises a network of 1395 nodes, 2950 links and a density of 0.003, underscoring the extensive reach and interconnectedness of research within this field.

3.2.1. Dual-map overlay

A dual-map overlay analysis was employed to identify the most productive and highly cited disciplines and journals within the realm of climate literacy research (Fig. 4). The dual-map overlay indicates that the most prominent disciplines in terms of citations in climate literacy research are those related to "Psychology, Education, and Social" on the citing side and "Environmental Science and Ecology" on the cited side. This prominence reflects a dynamic exchange of knowledge, where research in environmental science and

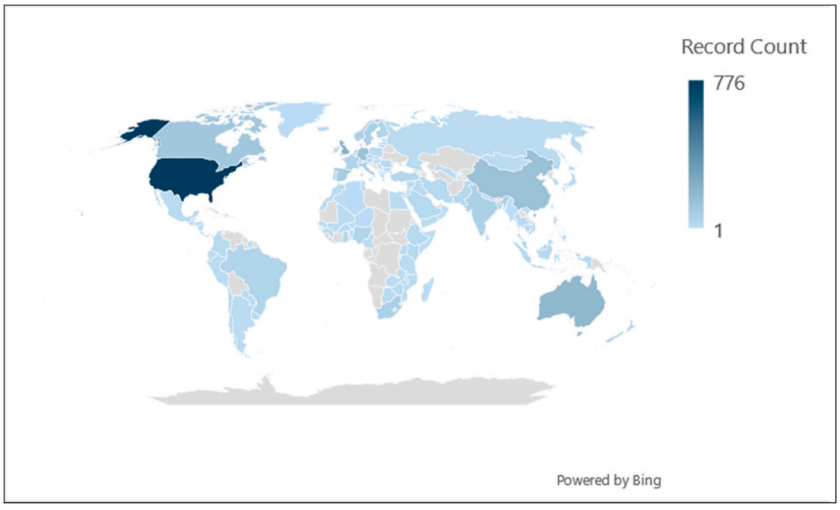

Fig. 3. Number of publications produced from countries around the world. Dark blue represents the highest total number of publications, whereas lighter shades represent fewer publications.

Table 1
Number of publications from the top ten journals containing research about climate literacy published between 1981 and 2024.

Publication Titles	Record Count	% of 2129
Climatic Change	57	2.677
Environmental Education Research	62	2.912
Frontiers in Psychology	21	0.986
Global Environmental Change Human and Policy Dimensions	26	1.221
International Journal of Climate Change Strategies and Management	19	0.892
International Journal of Environmental Research and Public Health	27	1.268
Journal of Cleaner Production	33	1.55
PLOS One	22	1.033
Sustainability	117	5.496
Wiley Interdisciplinary Reviews Climate Change	29	1.362

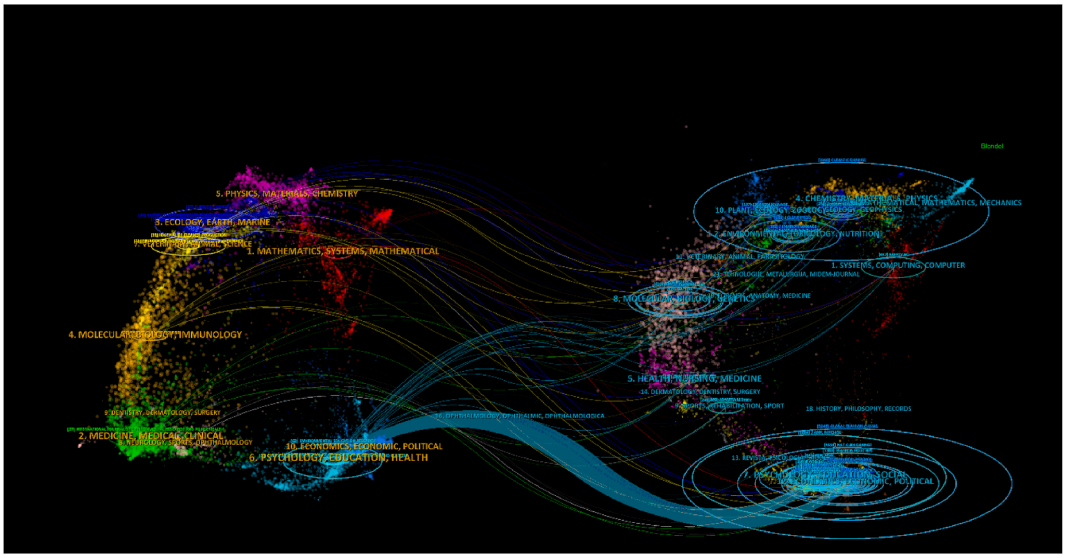

Fig. 4. Dual map overlay on climate literacy research. Points represent literature, ellipses represent groups of subject matter, and directional lines represent the connection between subjects. Each unique discipline is represented by a different color.

ecology informs studies in psychology, education, and social sciences.

3.2.2. Document Co-citation analysis

DCA provides a means to assess the frequency with which multiple documents have been co-cited by subsequent publications, thus yielding insights into the interconnectedness of knowledge (Fig. 5). This network is shaped by both citing and cited documents downloaded directly from the WoS database. The visualization presents a complex network of climate literacy research featuring 1106 nodes and 7426 links, indicative of a vast and interconnected field. The high silhouette score of 0.908 suggests that the research articles within each cluster share substantial thematic commonality, demonstrating a strong and cohesive grouping of topics. The harmonic mean of 0.9154 reflects the network's internal coherence, indicating a balanced citation spread across the papers. A low-density score of 0.0031 is characteristic of specialized research networks, where extensive direct citation connections between all papers are not expected, due to the diverse nature of the field.

3.3. Cluster analysis

A total of 13 co-citation clusters emerged from the analysis (Fig. 6). These clusters were identified and ranked based on their sizes, with the largest cluster labeled as #0. The circle size within each cluster reflects the degree of influence of the publications, with larger circles indicating higher citation rates. The lines extending from each cluster represent the duration or lifetime of the cluster. Notably, the size of each cluster corresponds to the number of publications it encompasses, with eleven out of the thirteen clusters comprising more than twenty publications, while cluster #0 being the most substantial in terms of the number of publications. Furthermore, the silhouette score for each cluster falls within a range from 0.818 to 0.999, signifying a commendable level of homogeneity among the publications within each cluster. Silhouette scores a range of −1 to 1, with values exceeding 0 indicating a high degree of homogeneity.

The major clusters that emerged from DCA. Cluster 0, labeled "bad news," encompasses a sizable collection of 129 documents, predominantly from 2018, with a strong internal consistency indicated by a silhouette score of 0.893 is presented in Table 2. This

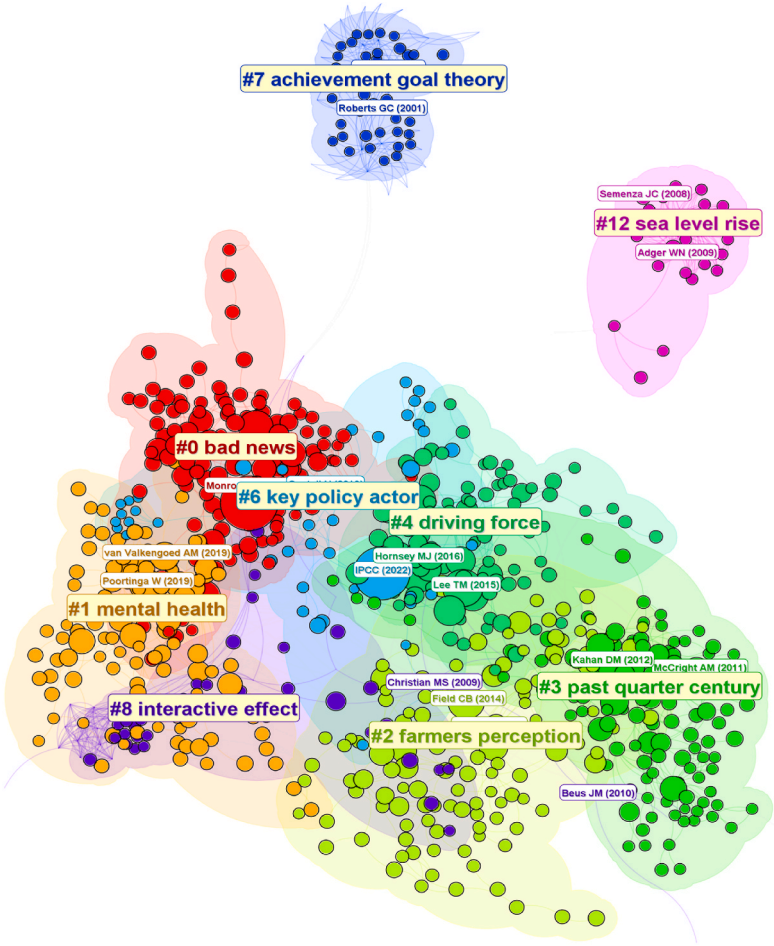

Fig. 5. Document Co-citation Analysis on climate literacy research.

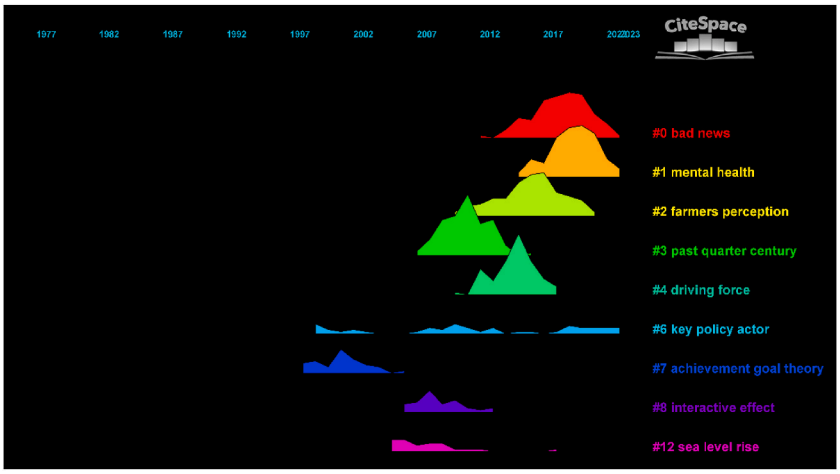

Fig. 6. Summary of 13 identified document cluster lifetimes (solid lines). Cluster labels were generated from CiteSpace. Circle size corresponds to cluster size (i.e. number of publications).

Table 2
The major clusters that emerged from Document Co-citation Analysis are presented here. Size represents the number of publications in a cluster, and the silhouette score indicates levels of homogeneity. Labels were derived from log-likelihood ratios (LLR).

Cluster ID	Size	Silhouette	Label (LLR)	Average Year
0	129	0.893	bad news	2018
1	124	0.938	mental health	2019
2	123	0.9	farmers perception	2015
3	119	0.96	past quarter century	2010
4	98	0.906	driving force	2014
6	48	0.958	key policy actor	2011
7	41	1	achievement goal theory	2000
8	35	0.915	interactive effect	2008
12	27	1	sea level rise	2007
22	14	0.976	organizational features stress	2000
32	8	1	safety performance	2006

suggests a concentrated exploration of the negative implications of climate discourse. Cluster 1, with the theme of "mental health," shows very high cohesion (0.938 silhouette score) among its 124 documents, mainly from 2019, reflecting the growing concern for the psychological effects of climate change. Similarly, Cluster 2's focus on "farmers' perception," consisting of 123 documents with an average publication year of 2015 and a silhouette score of 0.9, points to a significant body of research on agricultural stakeholders' views on climate change. The analysis presents a landscape where research themes are both varied and deeply explored, with some themes representing long-standing areas of focus while others indicate emerging trends, reflecting the field's dynamic nature as it adapts to the evolving challenges of climate change.

3.4. Individual analysis

3.4.1. Burstness

Table 3 presents the top ten references with a burst duration of more than 3 years in the context of Climate Literacy research. Each reference is associated with a 'Strength' value, quantifying the surge in citations over a period and signifying the paper's influence during that time. A higher strength value indicates a more pronounced spike in how frequently the work was cited. The 'Begin' and 'End' columns specify the years during which each publication's citation burst started and concluded. For instance Ref. [15], shows a strong citation burst starting in 2010 and tapering off by 2014, suggesting that during these years, Hulme's work was particularly influential and heavily referenced in subsequent research. Some publications [16–21], with an exceptionally high burst strength of 20.36 from 2017 to 2020 are indicative of works that have gained rapid and substantial attention in the scientific discourse of climate literacy during those specific years.

3.5. Sigma and centrality

Table 4 provides insights into the top ten references with the highest sigma values within the realm of climate literacy research. Sigma is a metric that assesses scientific novelty by combining centrality and burstness, measuring the degree of originality and the impact of a publication in the field. The centrality scores represent the degree to which individual articles are referenced alongside

Table 3
Top publications with the strongest citation bursts for the year.

References	Strength	Begin	End
[15]	11.75	2010	2014
[17]	4.21	2011	2014
[18]	12.68	2013	2016
[19]	11.62	2013	2016
[20]	11.48	2013	2017
[21]	10.04	2013	2017
[22]	10.82	2014	2018
[23]	9.85	2015	2018
[24]	10.35	2016	2020
[25]	10.08	2016	2019
[16]	20.36	2017	2020
[26]	14.71	2017	2021
[27]	7.81	2018	2021
[28]	9.79	2019	2021
[29]	4.68	2020	2022
[9]	10.21	2021	2022
[30]	10.33	2022	2024
[31]	4.22	2022	2024

Table 4
Document Co-citation scores for the top ten articles related to research on Energy Management Systems.

References	Centrality	Sigma
[26]	0.03	1.73
[16]	0.02	1.54
[22]	0.04	1.47
[9]	0.02	1.46
[20]	0.03	1.42
[32]	0.03	1.31
[33]	0.04	1.31
[34]	0.06	1.30
[35]	0.04	1.20
[36]	0.02	1.19

Table 5
The most influential publications in these domains.

Period	Focus	Key Publication
2010–2012	Cultural, Political and Ethical Dimensions Discussion	[15,17,18]
2013–2015	Impact of personal experiences and educational strategies	[22,24,25]
2016–2019	Knowledge and Empowerment	[16,26,30]
2020 - current	Emotional and Psychological Dimensions	[31]

others, with a higher score indicating a pivotal role in the research network [22]. demonstrates notable centrality with a score of 0.04, positioning it as a key node in the climate literacy literature network (see Table 5).

The sigma metric encapsulates both the centrality of an article and its citation burst intensity, offering a composite picture of its short-term impact and long-term relevance [26]. Stands out with a sigma score of 1.73, alongside a centrality score of 0.03, indicating that the work has not only been central to the field's development but has also experienced significant citation momentum within a given period.

These metrics collectively suggest a landscape in which certain studies act as foundational pillars of the climate literacy discourse, often serving as a basis for further research development. The integration of centrality and sigma scores reveals a nuanced hierarchy of influence, with works like [18] achieving the highest centrality score at 0.06, underscoring its integral position within the thematic network despite a relatively moderate sigma score of 1.30. These results highlight the multifaceted impact of key scholarly contributions to the evolving narrative of climate literacy research.

4. Discussion

This study aims to synthesize climate literacy research published between 1981 and 2024 using the WoS database and the scientometric tool, CiteSpace. This research seeks to answer three key questions: (i) What are the overall publication trends in terms of output? (ii) What are the central topics/clusters? and (iii) What are the most influential publications in these domains? In the following section, a thorough examination of the results will be provided, offering an in-depth analysis and a comprehensive exploration of the findings.

(i) What are the overall publication trends in terms of output?

A comprehensive analysis was conducted, incorporating descriptive and dual-map analysis, to provide a holistic view of publication trends in climate literacy research. The descriptive analysis encompassed an evaluation of the number of publications, the countries/regions involved, and the contributing journals and authors. This examination revealed 2129 publications with an h-index of 94. These publications have garnered 47,328 citations, resulting 22.23 citations per article. Notably, this body of research has exhibited a consistent upward trajectory from 1981 to 2024, illustrating the enduring relevance and growth of the climate literacy domain.

The trend illustrates that climate literacy has become an increasingly important field of study over the past few decades. The slow initial growth may have been due to limited public and scientific discourse on climate change during the early years. The significant growth in the mid-2000s may correlate with greater public awareness and policy focus on climate change, possibly driven by international agreements and the mainstreaming of climate issues. The IPCC AR4 played a pivotal role in increasing global awareness and stimulating a surge in climate-related publications, highlighting the critical need for climate action [37]. Moreover, the rise in extreme weather events, even those not directly attributable to climate change, has further heightened public awareness and perception, driving additional research in this domain [38].

The dramatic increase in the number of publications on climate literacy research after the 21st century, particularly the surge in 2015, may be attributed to several key factors. First, the global recognition of climate change as an urgent and critical issue has

intensified, driven by significant international events and agreements, such as the Paris Agreement in 2015, which mobilized global efforts to combat climate change. This period also saw an increase in funding and research initiatives focused on environmental education and public awareness, contributing to the rise in publications. Additionally, the development and dissemination of new educational frameworks and curricula aimed at improving climate literacy in schools and communities likely spurred academic interest and research output.

Furthermore, the research areas include the participation of 106 countries, with the United States of America, Australia, and England emerging as the primary contributors. The map suggests a disparity in the contributions to climate literacy research across countries. This disparity underscores potential challenges in climate change communication and education—areas critical for informed policy-making and public action. The lower publication counts in many developing nations suggest a need for increased investment in research capacity and knowledge dissemination to effectively address the global nature of climate change. Countries with burgeoning research outputs, such as the People's Republic of China, indicate a growing recognition of the importance of climate literacy and an investment in understanding and addressing climate issues. The data suggest that, while some regions are leading in climate literacy research, there is a significant opportunity for international collaboration to enhance global understanding and action on climate change.

The key journals driving climate literacy research have significantly contributed to the field's development. The journals listed span diverse fields including environmental science, education, psychology, sustainability, and public health, reflecting the interdisciplinary nature of climate literacy research. The prominence of "Sustainability" and "Environmental Education Research" indicates the significance of these journals as platforms for disseminating research on climate education and sustainable practices. The inclusion of "Frontiers in Psychology" and "Wiley Interdisciplinary Reviews: Climate Change" highlights that the psychological aspects of climate change and broad review articles that synthesizing knowledge across disciplines are also central to the discourse. The data from "PLOS One" and "Journal of Cleaner Production" indicate a focus on open-access publishing and practical applications of research, respectively. This spread highlights the importance of multidisciplinary approaches in addressing climate literacy and suggests that future research should continue to bridge multiple fields of study to tackle the complex issues of climate change.

The dual-map overlay revealed that articles focusing on climate literacy predominantly fall within the "Psychology, Education, Social" discipline and "Environmental Science and Ecology" disciplines. This trend highlights a crucial interdisciplinary dialogue, where the hard science of climate change is being translated into formats that are accessible and actionable within educational and social contexts. Studies in environmental science provide the empirical evidence and theoretical foundation that drive the development of educational content, strategies, and policies. Simultaneously, research in psychology and social sciences, which is more prominently cited, explores how this information impacts human behaviour and society—focusing on areas such as climate change communication, public understanding, and the psychological impacts of climate change. The prominent flow of citations from environmental disciplines to educational and social sciences indicates a research ecosystem that values empirical foundations as well as practical, human-centered applications. This synergy is crucial for designing educational programs that not only inform but also engage and motivate diverse audiences to take meaningful action on climate change.

(ii) What are the central topics/clusters?

To answer the second research question, a document cluster analysis was conducted and yielded a total of 13 co-citation clusters. According to the results, the top three dominant research topics and directions were "bad news," "mental health" and "farmers' perception". The robust silhouette values of these top clusters indicate a high level of internal consistency within each of them.

In cluster #0 labeled "bad news", the most frequently cited articles are authored by Refs. [9,30,39,40]. The average publication year of articles in this cluster is 2018. The majority of the article in this group contribute to the discourse on how climate change is taught and learned [9]. delves into this domain through a systematic review of research strategies, culminating the identification of educational practices that effectively communicate the complexities of climate change. Their work establishes a foundation for understanding the impact of educational interventions.

Extends this conversation by exploring the intersection of education and climate mitigation, positing that educational outcomes can significantly influence the adoption of climate-positive behaviors and policy adherence [39]. This perspective fosters a nuanced dialogue on the role of education not merely as a means of knowledge dissemination, but as a catalyst for tangible change. Further specializing the discourse [30], hones in on the younger demographic, advocating for climate change education that empowers children and youth. By giving this group, a "voice" and a "hand", the authors argue for a more participatory and action-oriented approach to environmental education, which not only informs but actively involves students in remedial activities.

Lastly [40], presents a reflective critique on the dichotomy of possibilities and perils in climate change education research. This contemplative piece assesses the potential of educational initiatives to foster transformative change while acknowledging challenges that could impede progress, including political, social, and economic barriers. Collectively, these studies underscore the critical role of education as a transformative tool in the context of climate change. They advocate for an integrative approach that combines rigorous systematic research with the innovation of pedagogical practices, aiming not only to enlighten individuals about climate change but also to inspire and mobilize collective action towards mitigation and adaptation strategies. This synthesis of contributions foster a deeper understanding of both the potential and the challenges inherent in climate change education.

Cluster #1 mental health focuses on the human dimension of climate change, particularly on the psychological aspects, perceptions, and behavioral responses. The average year of publication for articles in this cluster is 2019. Study by Ref. [36] provides a pan-European analysis that highlights the diversity in climate change perceptions influenced by personal beliefs. Complements this by identifying the motivational precursors that drive climate change adaptation behaviors, which is crucial for designing impactful

interventions [41]. Highlighting the emotional toll of climate change, uncovers the extent of climate anxiety among children and young people, linking it to their perceptions of governmental inaction [42]. This line of research is vital in understanding the psychosocial impacts of climate policy (or the lack thereof) on younger demographics.

In a similar vein [43], bridges the gap between climate concern and climate action, analyzing how personal values, worry, and responsibility culminate in pro-environmental behaviors. Lastly [44], expands on the theme of climate anxiety, exploring its broader psychological implications and the consequential behavioral patterns it may induce. Together, these studies present a comprehensive narrative that emphasizes the importance of psychological factors in understanding and addressing climate change. They underscore the necessity for targeted communication and policy strategies that resonate on a personal level, thereby fostering a more robust engagement with climate action.

Finally, in Cluster #2 (farmers perception), the central theme revolves on farmers' perceptions of climate change and how these perceptions align with actual climatic data, as well as the identification and implementation of adaptation strategies. Notably cited articles within this cluster include contributions by Refs. [24,27]. The average year of articles in this cluster was 2015.

Delve into the correlations between what farmers believe about climate change and the actual temperature and precipitation trends, with a particula focus on how these perceptions influence the use of irrigation and are shaped by existing climate beliefs [27]. Broadens the scope by examining public perceptions, potentially offering a comparative backdrop to farmers' viewpoints and exploring the psychological underpinnings of how climate change is conceptualized by different communities [24].

In the early 2010s, extreme weather events such as the 2010 Pakistan floods, Russia's 2010 heatwave, and Superstorm Sandy in 2012 heightened public awareness of climate change [45–49]. Simultaneously, grassroots activism gained momentum with movements like 350.org and mass protests such as the 2014 People's Climate March, which mobilized millions to demand stronger climate policies, further amplifying global awareness [50,51]. On the policy front, the lead-up to the 2015 Paris Agreement, supported by summits like Copenhagen in 2009 and Durban in 2011, put climate change at the center of international diplomacy [51]. National initiatives like Germany's Energiewende and the U.S. Clean Power Plan, alongside rising corporate responsibility, as seen with Unilever's sustainability goals and Tesla's electric vehicle push, helped establish climate change as a critical business and economic issue [52–55]. These combined efforts promoted the idea that addressing climate change was not only an environmental necessity but also an economic opportunity.

In a similar [56] anchor their study in the context of southwestern Nigeria, juxtaposing the perceptions of smallholder farmers with meteorological data to assess the accuracy of local climate change knowledge. This comparison is crucial in understanding how farmers interpret their lived experiences against the backdrop of scientific data. Complementing these insights [57], turn to the farmers of North-West Ethiopia, investigating not only their perceptions of climatic variations but also the concrete adaptation strategies employed to cope with these changes.

Together, these articles emphasize the importance of integrating farmers' perceptions with empirical climate data to foster a more robust understanding of climate change impacts on agriculture. This synergy is key to tailoring effective adaptation strategies that resonate with farmers' experiences and beliefs, ultimately aiding in the development of targeted interventions to bolster agricultural resilience in the face of a changing climate.

Future research across the three clusters should adopt a transdisciplinary approach, integrating educational strategies with digital innovations for climate change communication (Cluster #0), developing interventions to address climate anxiety and its impacts across cultures (Cluster #1), and combining scientific data with local knowledge to craft effective farmer-centric adaptation practices (Cluster #2). Studies should evaluate long-term outcomes of education on behavior and policy, assess the effectiveness of psychological support mechanisms for climate-related stress, and understand the socio-economic factors influencing farmers' adaptive strategies to facilitate informed decision-making and robust climate resilience.

(iii) What are the most influential publications in these domains?

To address the third research question in our study, we employed a Document Citation Analysis (DCA) on relevant articles, focusing on three primary metrics: burstness, centrality, and sigma. Burstness identifies surges in citations for individual articles, highlighting periods of increased citation activity. Centrality scores determine the influence of articles within a research domain, with higher scores indicating greater influence. Sigma combines centrality and burstness to assess the scientific novelty of the articles.

The progression of climate literacy research over time demonstrates a clear evolution in focus, beginning with studies on the cultural, political, and ethical dimensions of climate change, which laid the groundwork for subsequent investigations into personal experiences and educational strategies. Early research [15], explored the political and cultural barriers to understanding climate change, revealing the deep divisions in public opinion and political action. This foundational work enabled later studies [24] to delve into how personal experiences with climate impacts influence public perceptions and behaviors. As a result, researchers were able to build a cohesive narrative, moving from theoretical and cultural discussions to more practical studies on educational interventions, which have been instrumental in shaping public knowledge and engagement with climate issues. This layered approach has collectively contributed to the growing body of knowledge that informs both climate change communication and policy-making today.

The analysis of document bursts demonstrated emerging research topics and the gradual replacement of earlier publications with more recent ones. The initial burst started in 2010 [15]; began the discussion by exploring the complex cultural, political, and ethical dimensions behind varying climate change beliefs. Subsequent studies by Refs. [17,18] highlighted the gaps in public scientific understanding and the increasing politicization of climate change, respectively [17,18]. Further examined how cultural values influence perceptions of climate risks [20].

By the mid-2010s, the focus shifted towards the impact of personal experiences and educational strategies on climate change

perceptions [22]. questioned the influence of personal experiences, while [24,25] investigated educational strategies to counter skepticism and track public perceptions over 25 years, respectively [22,24,25]. [16] identified global predictors of climate change awareness and risk perception.

The latter half of the decade saw a continued emphasis on the role of knowledge in shaping public perceptions, with [26,28] focusing on this aspect. By 2019, the educational focus expanded to include empowering youth, as advocated by Ref. [30]. By 2020, discussed the emotional impacts of educational experiences on responses of climate change [31].

The 10 publications with the highest sigma and centrality scores provide a comprehensive examination of the various dimensions of climate change awareness, perception, and education, highlighting the complexity of public engagement with climate issues. This selection includes studies that explore the psychological aspects of climate belief, effective educational strategies, the impact of political polarization, and public skepticism towards anthropogenic climate change.

5. Conclusion

This compilation identifies significant research gaps and prospective directions within a cluster of related disciplines. The selection of papers from the Web of Science (WoS) database may introduce biases; however, WoS is recognized for its high publication standards (Bar-Ilan, 2007; Kulkarni, 2009). Future research could benefit from comparing WoS with other databases to identify any discrepancies. Although the use of CiteSpace software for analysis may include some irrelevant subjects, it offers reproducibility. Future studied should consider stricter keyword searches or manual reviews of exported data to minimize the inclusion of irrelevant studies.

Future research on climate literacy should strategically address several key areas to enhance understanding and effectiveness. An interdisciplinary approach is crucial, integrating insights from environmental science, psychology, sociology, education, and communication studies to develop educational programs that address the cognitive, emotional, and social dimensions of learning about climate change. Investigating the impact of digital media on public understanding of climate science and environmental policies is also vital, given the significant role media plays in information dissemination.

In future studies, conducting a correlation or regression analysis could be beneficial to explore the relationships between global environmental policies, funding availability, and the surge in climate literacy publications. This would provide a more nuanced understanding of the factors driving these trends across different countries.

There is a pressing need to focus on cultural and regional differences by developing localized and culturally sensitive education strategies that consider the specific impacts of climate change on different regions. Furthermore, linking climate literacy to behavioral outcomes is essential; research should aim to understand how increased knowledge can lead to pro-environmental behaviors and identify the most effective strategies for translating knowledge into action.

Evaluating the effectiveness of existing educational programs is necessary to determine which strategies best enhance climate literacy. Research should also focus on creating and testing age-appropriate educational materials targeted at different age groups, especially young children and adolescents, to foster early awareness and engagement. Additionally, examining the relationship between climate literacy and public support for environmental policies can provide insights into how education influences public and political advocacy for sustainable practices.

Addressing misinformation and skepticism is imperative, given the rise of misinformation. Studies should explore its effects on public perception and develop strategies to combat climate change denial. Longitudinal studies would be beneficial for tracking changes in climate literacy over time, particularly in response to major climate events or policy shifts. Lastly, exploring innovative educational techniques, such as gamification, virtual and augmented reality, and project-based learning, could significantly enhance engagement and understanding of complex climate issues. These focused research efforts are essential for developing more resilient and informed communities ready to tackle climate challenges.

CRediT authorship contribution statement

Rahmawaty: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mohd Hasmadi Ismail:** Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization. **Abdul Rauf:** Validation, Supervision, Resources, Investigation, Conceptualization. **Muhammad Fuad Abdullah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Mohd Iqbal Mohd Noor:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Amira Mas Ayu Amir Mustafa:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Seca Gandaseca:** Validation, Supervision, Resources, Investigation, Formal analysis. **Mahawan Karuniasa:** Writing – review & editing, Validation, Resources, Formal analysis. **Yekyoum Kim:** Writing – review & editing, Methodology, Formal analysis. **Mohd Nazip Suratman:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Siti Aekbal Salleh:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Peter Aning Tedong:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing

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