Discover Sustainability

Review

Global research trends in Environmental adaptation techniques focusing on climate change through scientometric lens

G. Shyamala[1] · R. Gobinath[2] · B. Hemalatha[3] · DivyaSri Akkalla[4] · S. Shenbaga Ezhil[5] · V. Sathya[6]

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Abstract
Climate change is a significant threat to ecosystems and communities, and challenges global sustainability; therefore, more research on climate change adaptations should be conducted. This scientometric study presents databases on global trends in academic research, specific contributions, and thematic evolution of environmental adaptations to climate change. Using the Scopus database of publications, this study focuses on publications between 2009 (January) and 2024 (August), with an emphasis on the interpretation of primary research interests, authors, contributions from countries, and collaborative networks. According to the findings, there has been a shift in focus to more adaptive management in agricultural and biological diversity practices, with more emphasis on the integration of ecological, technological, and social science disciplines. This work also reveals that countries have gaps in regional research, especially in developing countries, and highlights the need to work collectively across the globe. Through citation analysis, thematic evolution, and future research recommendations, this study enriches the knowledge of the line of research on environmental adaptation and underlines its significance in addressing climate change effects.

Keywords Environment · Adaptation · Climate change · Sustainable development · Diversity · Evolution

1 Introduction

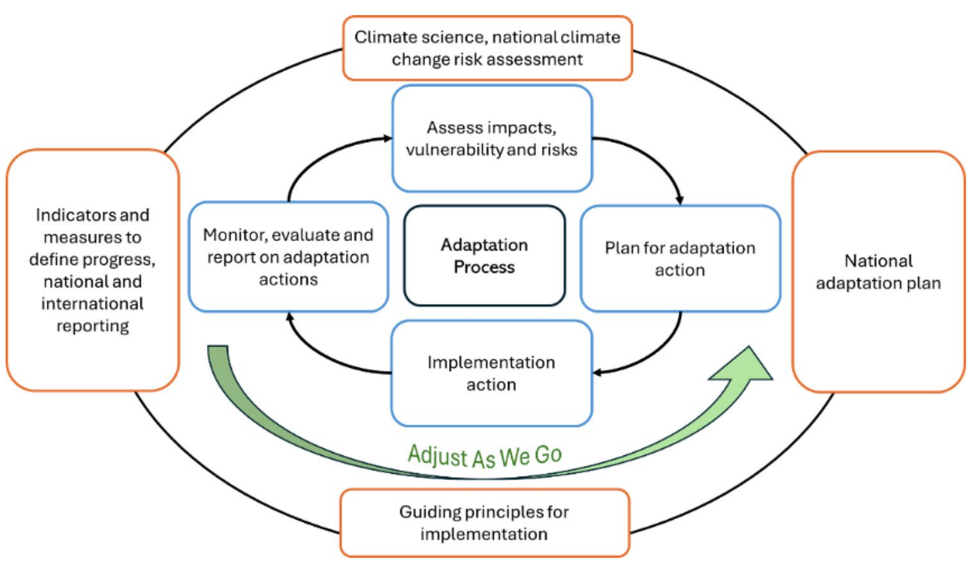
The term 'climate change' describes substantial and enduring changes in global weather patterns [14]. Global warming, which occurs when the Earth's atmosphere holds more heat from the sun, is a major component of this process [15]. A globally prevalent characteristic is the greenhouse effect, in which some constituent gases of the atmosphere hold infrared radiation and fail to emit it into space, thereby warming up planets. Greenhouse gases, such as carbon dioxide (CO2), methane (CH_3), and water vapor (H_2O), warm up by trapping incoming infrared radiation emitted by the earth's surface. This is an important regulation of the Earth's temperature for habitability, but it results in excessive warming when greenhouse gas concentrations surpass natural levels [14]. However, through our activities, we are altering conditions that are comparable to putting on super-insulating layers, which you remember makes the body too warm. In essence, this additional heat brings about several inconveniences, including an increase in the occurrence of cyclones and typhoons due to the warm oceans and melting of polar ice caps that cause sea level

✉ G. Shyamala, civilshyamala@gmail.com | [1]Department of Civil Engineering, SR University, Warangal, Telangana 506371, India. [2]University Center for Research and Development, Chandigarh University, Mohali 140413, India. [3]Department of Civil Engineering, St Peter's Institute of Higher Education and Research, Chennai 600077, India. [4]Center for Informetrics and Statistics, SR University, Warangal, Telangana 506371, India. [5]Department of Mathematics, Jeppiaar Institute of Technology, Chennai 631604, India. [6]Department of Computer Science and Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai 600062, India.

rise and flooding in some regions with populations. To avoid aggravating this situation, it is necessary to determine its causes and factors. In this regard, one can help manage the situation and reduce the emission of carbon in the atmosphere, which has caused extra warmth on our planet. Changes in Earth's climate on a local, regional, or global scale are included in the term "climate change," which can also refer to the effects of these changes. Human activity since the preindustrial era (roughly 1850 onward) includes burning fossil fuels and deforestation, which has significantly increased the amount of carbon dioxide in the atmosphere [4, 24]. The effects of climate change are felt globally, endangering the infrastructure, human populations, and ecosystems. Food and water insecurity has been established to worsen owing to extreme and increasing weather conditions, negatively affecting structures, means of living, and health. Cumulative impacts such as these make it difficult for different states to foster the attainment of Sustainable Development Goals (SDGs). Furthermore, available evidence suggests that climate change leads to insecurity, causes people to flee, and expands conflict. This study presents a scientometric analysis of global research trends in environmental adaptations to climate change. By examining the volume, impact, and collaboration patterns of scientific publications in this field, this study aimed to identify key research areas, influential publications, and the geographical distribution of adaptation research. Additionally, it seeks to highlight the evolving focus of adaptation strategies from traditional practices in agriculture and water management to innovative solutions in urban planning and ecosystem restoration.

The adaptation to climate change shown in Fig. 1 minimizes the impact of climate change, whereas the enhancement of system frailty increases the capacity of all systems to cope with shocks and pressures related to climate change. Changes in procedures and practices, in addition to actual physical changes in the environment, are required to effectively manage climate impacts by reducing possible harm and exploiting opportunities resulting from climate change [20]. This means that millions of people will continue to experience the impacts of climate change if appropriate adaptation is not implemented, leading to more impacts resulting from each degree of global warming. Adaptive Management: Adaptive management practices for climate adaptation include those that change with new knowledge of climate and observed changes in the environment. Thus, practices might range from adjusting an agricultural process as a result of changing precipitation rates or redrawing a system to protect the coast due to new water levels and storm occurrence. The addition of real-life adaptive management case(s), such as changing water delivery information with drought data or changing a plan on how to prevent wildfires with changes in weather information, would be useful to readers. This would further cement adaptation as a process, not a product, and reiterating would introduce tangibility into the risk resilience of climate adaptation. Adaptive management is important in dynamic environments characterized by unpredictable changes and increased occurrence of climate variations. In this case, both primary- and secondary-level prevention measures and strategies should be taken, as the loss of ecosystem services resulting from irreversible changes will be dangerous because ecosystems are already under unparalleled pressure that may surpass their coping capacity [3].

Fig. 1 Adaptation process



2 Sustainable development goals and climate change

Climate change can reverse most of the Sustainable Development goals; however, climate solutions can support all the goals but can hinder goal number 12 out of 17. A specific climatic goal or climate change (SDG 13) should be integrated into the SDGs because climate change threatens the global achievement of all SDGs. A report by [16] states that in this decade, there is an acute and chronic need to adapt to climate change to protect 68% of the SDG targets.

Notably, although the SDGs seek to respond to current environmental imperatives, the emphasis placed on modern models of economic development does not allow the SDGs to adequately address climate challenges and related injustice [33]. This contradiction underlines the need for further and deeper sustainable development strategies and climate change actions. Furthermore, the renewable energy industry has grown rapidly due to the effects of climate change and the challenges of sustainable development goals with the help of Artificial Intelligence; however, the possibility of reaching the SDGs objectives in this field has not been fully researched [23].

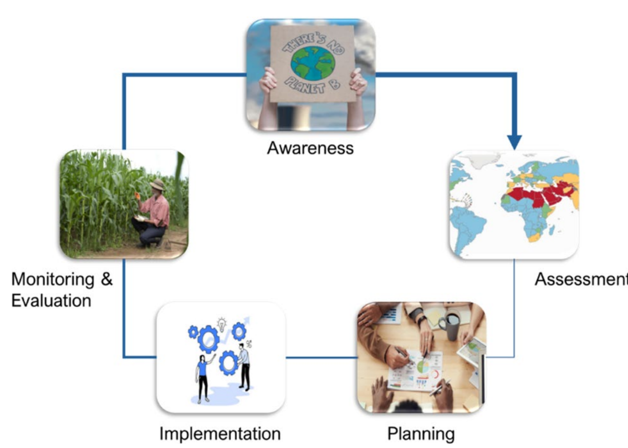
Overall, this means that effective advances in addressing climate change and achieving development goals depend on enhanced interdisciplinary cooperation in governance. There is a need to prioritize the adaptation of key sectors, including wetlands, rivers, cropland, construction, water, electricity, and housing in the most vulnerable countries in order to protect sustainable development by the year 2030, as proposed by [16]. Applying geospatial technologies enhanced by ICT coupled with advanced analytics for modeling can offer tools for evaluating, monitoring, and decision-making in response to SDG indicators [28]. In the end, it is vital that the two strategies, namely, mitigation and adaptation, be integrated together so as to realize the goal of the SDGs within the context of climate change [35].

3 Environmental adaptation

Environmental adaptation entails biological, behavioral, and structural changes that enable organisms, species, and ecosystems to survive and reproduce. Growing awareness of global environmental changes, particularly those induced by humans, has heightened the interest in studying adaptation within ecosystems and societies. Thus, adaptation is an evolutionary response to environmental pressure [10]. Technological adaptation often involves societal responses to environmental changes such as climate change, deforestation, and pollution.

Biological systems adapt to physical changes, enabling species to cope with adverse or fluctuating conditions. For example, arctic foxes and polar bears possess thick fur and fat layers that maintain warmth in cold environments [15]. Desert flora has adapted to the arid environment; for example, cacti possess leathery skin to minimize water loss and long taproots to access deep soil moisture [30]. Organisms can adapt to behavioral changes; for example, certain bird species travel several kilometers to find regions with a more moderate and favorable climate during winter [6]. Morphological adaptations include physiological responses such as hibernation and energy conservation during resource shortages or adverse climatic conditions. A sustainable solution for environmental adaptation is shown in Fig. 2. Short-term environmental changes, such as climate change or habitat destruction, can overwhelm organisms

Fig. 2 Sustainable solutions for environmental adaptation



and lead to extinction. Species with short generation times or high genetic variation can adapt more quickly to new conditions than species with longer generations [34].

Historically, humans have adapted to environmental changes for survival. Desert societies have developed irrigation for farms, while modern societies employ advanced agricultural techniques to address climate change [26]. Climate change poses significant concerns to humanity, necessitating mitigation and adaptation strategies. Cities such as New Orleans face severe threats from rising sea levels, prompting the construction of protective structures, while Venice is also developing similar defenses. Farmers in arid regions have adopted drought-resistant crops and water harvesting methods [1], and globally implement strategies to reduce carbon footprints, promote green energy use, and ensure funding for climate change adaptation projects [31]. These strategies improve social adaptation to change while minimizing the impact on environmental and human well-being. Ecosystems are composed of living organisms and their environments, which evolve as a result of species modifications, food chains, or other processes. For example, corals experience "coral bleaching" owing to warmer water temperatures. However, if environmental changes exceed an ecosystem's adaptive capacity, biodiversity loss and ecosystem degradation occur [13]. Human actions have led to various changes in ecosystems that require adaptation. Habitat enhancement, species preservation, and pollution reduction can help ecosystems mitigate environmental changes. In contrast, aggressive activities such as deforestation and overfishing diminish ecosystems and impair their recovery capacity [25].

4 Adaptation planning and implementation

Climate change adaptation refers to coordinated efforts to protect or improve development activities against the negative impacts of climate change, minimize vulnerability, and adapt systems to changing climate regimes in a manner that will be sustainable in the future. Adaptation also prevents loss of life and financial loss because climate impacts are harnessed and an action plan is made. Such ecological systems offer sources, such as water, air, and food. Adaptation planning helps to retain these services during environmental changes. When applied, adaptation planning helps establish long-term strategies to help communities cope with adverse situations. Cooperation plays a key role in the process of sustainable development because the growth of the economy and development should go hand in hand with the reduction of human susceptibility to the effects of climate change. The strategies of the adaptation and implementation frameworks are illustrated in Fig. 3.

The "Adaptation Planning and Implementation Framework" is a life cycle of seven approaches/implementation strategies to embrace effective conservation and adaptation to the changing environment. The steps involved in achieving this are as follows:

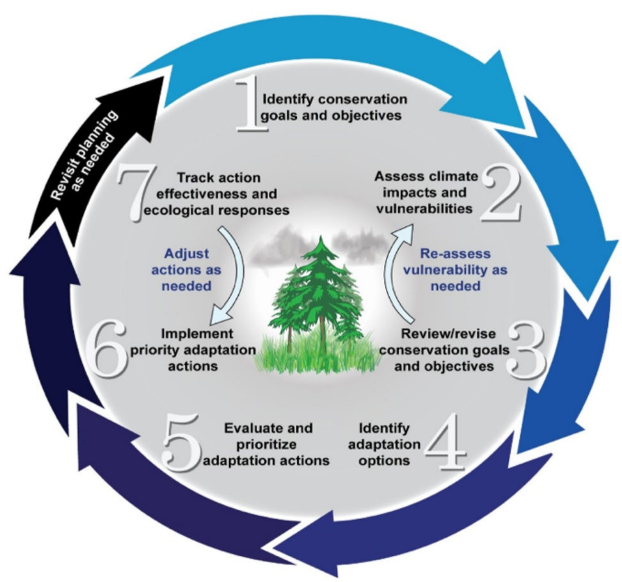


Fig. 3 Adaptation planning and implementation [22]

4.1 Identification of conservation goals and objectives

At this broad stage, particular areas of conservation concern are outlined to achieve other environmental goals and the future impacts of climate change. They are strategic, specific, measurable, achievable, relevant, or realistic and are based on the requirements pertinent to the ecosystem, species, or community at hand. These objectives give direction to the adaptation efforts needed, for example, to save endangered species, preserve biodiversity, or use resources sustainably. These goals help to focus on agendas and resource utilization appropriately, which forms the necessary foundation for the entire adaptation planning process.

4.2 Transform mitigating climate change and adapted impairments

In this step, a comprehensive evaluation was made of the effects of climate change on the conservation objectives envisaged and on different systems, species, or groups. It covers current climate data, climate forecasts, and aspects that are vulnerable to climate change. This assessment is ideal for determining how much of a threat the community experiences to determine exactly where to focus on adaptation efforts. Recalculation is important for understanding the changes in conditions and other data that may appear over a given period.

4.3 Review and revision of conservation goals and objectives

From the results of the vulnerability assessment, one can check the goals and objectives set alongside the current conservation status and make changes when needed. This additional step helps to maintain current goals and realistically provides updated information on climate risks and risks/resilience. It may involve repositioning goals or objectives as new success standards, changing goals or objectives, or adopting new goals or objectives. Updating goals assists in anchoring the adaptation plan with current information, as well as tailoring the plan to tackle current challenges better and thus enhance resistance to future changes.

4.4 Identification of adaptation options

Here, it is about generating and selecting several possible adaptation activities that may contribute to meeting changed conservation objectives. This involves defining measures and exercises that can reduce the effects of climate change or strengthen aspects that may be negatively affected by climate change. Adaptation measures can include structural measures such as the construction of structures to changes in policies or community measures. The aim is to reach a clear list of actions that provide different options for reaching set goals.

4.5 Evaluation and prioritization of adaptation actions

The possible adaptation options are then prioritized, depending on the practicability, efficiency, economic value, and advantages of the suggested plan. In this step, a relative evaluation or ranking is performed to prioritize actions based on the benefits achieved compared with the costs and risks incurred. Considerations such as resource availability, technological needs, and stakeholder endorsements are typically considered. This step means that instead of simply listing the key activities, it is an ideal strategy to prioritize them to avoid wasting scarce resources and ensure that efforts are directed towards the most pressing needs in the course of implementing the strategic plan.

4.6 Implementation of priority adaptation actions

After prioritization, we applied adaptations of choice to the constructed H-score model. This includes identifying the resources required to undertake the actions outlined above, the roles that will be played by who, and the timelines within which to implement the actions. These may include capital development projects, system and policy change initiatives, site rehabilitation, or community outreach. Successful and harmonious coordination of implemented actions with different stakeholders such as government departments, non-governmental organizations, and local people will be practical and possible to make implementation beneficial for meeting the set goals.

4.7 Tracking action effectiveness and ecological responses

An evaluation is important to ensure that the impact of the implemented adaptation actions is observed. This step involved implementing the processes and structures for monitoring, data collection, and assessment of the ecological and social impacts of the implemented adaptation measures. They say that monitoring pinpoints the successes that were made to understand, the challenges that emerged, and the areas that require improvement. The evaluation is also valuable for presenting information that helps managers continue the adaptation process today and for designing other actions for tomorrow. This allows for a constant assessment of the changing environment and new risks and threats, to which strategies can be adjusted.

When operating within the framework of the adaptation process, planning should be revisited and changed multiple times. This includes a periodic check on all parts of the framework, including goals and objectives, and the strategies used in implementation to reflect on climate data and ecological changes as well as stakeholders. This approach enables the accreditation process to be evolutionary in nature, thus making the adaptation process more fluid in the face of emerging challenges and opportunities. This creates the long-term sustainability of the structure when exposed to climate change because of the flexibility of the framework. The adaptive actions implemented in different sectors, such as water supply, ecosystems, infrastructure, and agriculture, are shown in Table 1.

5 Technological and innovative approaches to adaptation

Technological innovations are vital for adapting to environmental challenges such as climate change, resource depletion, and natural disasters. Traditional strategies have proven to be inadequate for rapid environmental changes, and technology-driven solutions are crucial for improving resilience and ensuring the sustainability of human and natural systems. Technologies such as AI, data analysis, renewable energy, and biotechnology enhance tools and methods for anticipating, mitigating, adapting, and alleviating the impact of environmental stressors [21]. Climate change has driven technological adaptation mechanisms; as the temperature increases, it alters rainfall patterns, and the increased frequency of abrupt climate events, such as floods or droughts, poses significant challenges to global communities [32]. Rising sea levels increasingly endanger coastal cities, while agricultural regions face disruptions in growing seasons and water supply. Modern technologies offer rapid and efficient solutions for these emerging threats.

Research shows that environmental monitoring and disaster management increasingly rely on artificial intelligence and big data, allowing more accurate and timely forecasting of risks, such as floods, droughts, and wildfires. These systems are incorporated into natural disaster warning systems to help governments and communities mitigate the impacts on vulnerable populations [27]. AI significantly improves the effectiveness of adaptation measures, enabling real-time solutions to various environmental issues. Developing climate-resilient infrastructure is crucial for mitigating community exposure to climate-related disasters. Metropolitan cities use techniques such as permeable pavements and green roofs to manage stormwater and flooding. Furthermore, advanced water management systems and efficient energy use in city construction allow cities to adapt to changes in temperature and precipitation, while reducing emissions [11]. To adapt agriculture to climate change, climate-smart agriculture has driven advances in precision agriculture, genetically modified crops, and drip-irrigation systems. These technologies help farmers mitigate climate-induced risks by optimizing resource use and producing resilient crops, thereby sustaining agriculture without causing environmental harm [8]. These innovations are crucial for sustaining agricultural productivity and rural economies in areas facing water scarcity and unpredictable weather.

Technology transfer is crucial for adaptation measures at the international level, as acknowledged by the Paris Agreement, which underscores the importance of transferring technology from developed to developing countries to enhance their adaptive capacities. Knowledge sharing enables countries to implement technologies that address both national and international environmental challenges [12]. Technological and innovative adaptation measures are crucial for increasing environmental changes. The use of technologies in infrastructure, agriculture, and disaster response can mitigate the risks of climate change, reduce vulnerability, and improve resilience. As climate change progresses, these innovations will be pivotal in preventing adverse climate change.

Table 1 Application of traditional and local knowledge in climate change adaptation across different regions (TEK stands for traditional ecological knowledge) [17]

Location	Sector	Approach and strategy	Adaptive action implemented	Institutions	References
Southern Kimberley, Australia	Water supplies	• Define vulnerabilities • Increase adaptive capacity	• Compile observed changes • Increase monitoring • Manage water resources • Review TEK	Universities; NGOs; United Nations University	Green et al. (2010); Prober et al. (2011); Leonard et al. (2013)
Trinidad, Bolivia and northern central Bolivia	Ecosystems, agriculture	• Reduce vulnerability	• Revive "camellones" (earthen platforms) TEK • Reduce erosion • Document local observations	Oxfam International; NGOs; Bolivian government; Food and Agriculture Organization	Oxfam International (2009)
Pinoleville Pomo Nation (California, USA)	Infrastructure	• Mitigation: solar power • Increase adaptive capacity	• Co-design infrastructure • Address insufficient capital • Address water shortages and energy needs	Universities; NGOs; Housing and Urban Development	Shelby et al. (2012); Pinoleville Pomo Nation Housing flyer (2013); Redsteer et al. (2013)
Fiji	Ecosystems and water supply	• Define vulnerabilities • Increase adaptive capacity	• Recognize TEK • Enable adaptive decision making • Enhance community awareness • Participate in development	Australian Agency for International Development; Fiji Department of Environment; University of the South Pacific	Dumaru (2010)
Kenya, Tanzania, Malawi, Zimbabwe, southern Zambia	Agriculture	• Define vulnerabilities • Increase technical capacity • Increase adaptive capacity	• Use drought early warning • Apply TEK • Develop novel reporting • Compile observed changes • Harvest rainwater • Change tilling practices • Use appropriate crop varieties	University of Cape Town; University of Nairobi; The United Kingdom's Department for International Development; Canada's International Development Research Centre	Changa'a et al. (2010); Mugabe et al. (2010); Kalanda-Joshua et al. (2011); Majule et al. (2013), Masindel et al. (2013)
Reservation lands (western USA)	Health, water supplies, environment	• Define vulnerabilities and impacts • Increase adaptive capacity	• Compile observed changes • Utilize environmental legislation • Review indigenous knowledge • Analyze local meteorological data • Analyze historical/legal context • Increase monitoring	Universities and affiliated NGOs; tribal offices; federal agency research	Redsteer et al. (2010); Doyle et al. (2013); Gautam et al. (2013)

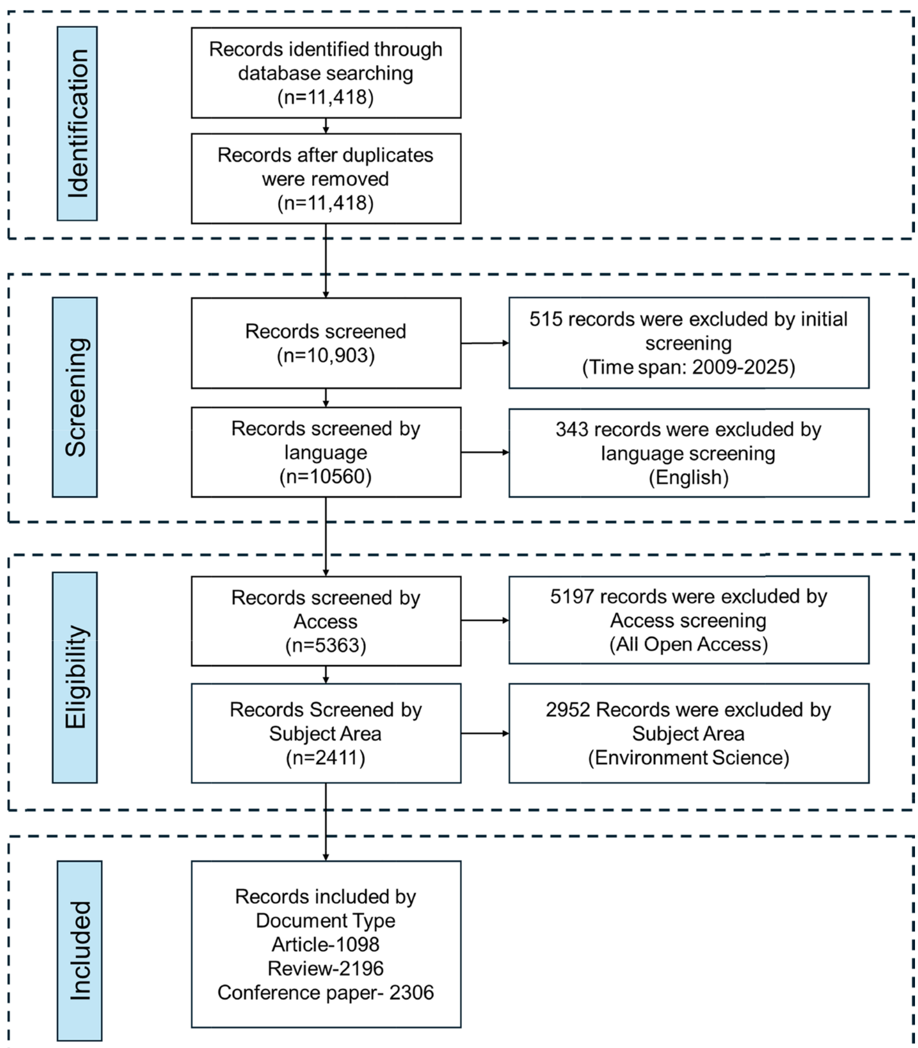
6 Global research trends in climate change adaptation

Global research trends in climate change adaptation were studied using a scientometric lens. Scientometric studies have been conducted to understand research related to the environment by many researchers. They found that there has been a significant increase in the number of publications and research activities on environmental management, environmental footprint, and environmental health inequalities over the past few decades [2, 18–36]. In general, citation databases such as Scopus, Web of Science, PubMed, Dimensions, and Openalex are used to search for keywords in that specific domain. The data obtained through the search were then analyzed and visualized using a bibliometric process. In this work, we have used Scopus as database for the process owing to its versatility, curated content and constant updates, recently its being the pet of scientometric researchers and many researchers use Scopus as search database [5, 29].

7 Methodology

The Prisma flow chart shown in Fig. 4 demonstrates how the comprehensive literature search was conducted, providing readers with a clear understanding of how the final data set was compiled for scientometric analysis [19]. It visually represents the identification, screening, eligibility, and inclusion of studies, thereby improving the credibility and reproducibility of the research. By detailing how studies are included or excluded, selection bias is minimized and a systematic approach to data collection is ensured.

Fig. 4 PRISMA flow diagram for the selection of research articles



The methodology includes consideration of potential limitations and biases in the study, such as limitations in database coverage or language restrictions. Overall, this section plays a critical role in ensuring the reliability and reproducibility of scientometric analysis, laying the foundation for the study's results and discussion.

Search Query: (TITLE-ABS-KEY ("environment") AND TITLE-ABS-KEY (adaptation) AND TITLE-ABS-KEY (climate change)) AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE, "English") AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (SUBJAREA, "ENVI") AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re) OR LIMIT-TO (DOCTYPE, "ch")).

The search strategy was described, including specific keywords, timeframes, and filters used to retrieve relevant publications. This was followed by a description of the data collection and inclusion criteria, ensuring that only pertinent, high-quality data were analyzed. The research design and scientometric approach pertaining to the constraints of the research, data collection, data processing, and visualization are shown in Fig. 5.

This methodology provides a systematic way to conduct research and data analyses in an orderly manner. It starts by defining the research parameters where researchers define a certain research topic and set their research question, choose the field to research, determine relevant keywords, evaluate any limitations of the study, and determine the appropriate databases to use. Second, the data collection stage involves obtaining the required data and transforming them into a form that is easily manageable, similar to a CSV file. After the data were collected, data processing was performed, during which bibliometric analysis tools, such as VOSviewer, CiteSpace, Origin Pro, and Tableau, were employed to identify the patterns of the analyzed data. VOSviewer and CiteSpace are the two most commonly used research tools for scientometric analysis because of their ability to represent complex bibliometric information. VOSviewer is suitable for the interactive data mapping of co-authorship networks, co-citation networks, and keyword co-occurrence. One tool builds clear and simple figures, enabling researchers to understand the relations between authorship, affiliation, and topics in a given set. This makes it suitable for analyzing the shared and temporal organization of a research discipline. In contrast, CiteSpace aims to define major trajectories and points of cognitive shift across time and recognize the development of research themes and emergent fields. Therefore, CiteSpace makes it easy to examine citation bursts and landmark articles to generate insights into the understanding of the dimensions of a given field [9]. For example, the software has already been applied in fields such as Environmental, Social and Governance research [7], as well as in the research of online role-playing games [8], which proves its significance in identifying topical changes and new trends. This step-by-step approach to handling and analyzing data in research makes it clear, organized, and efficient. Figure 6 shows the research trend analysis results obtained in this study.

From January 2009 to August 2024, the study presents bibliometric data, encompassing the following: the dataset includes 447 sources and 2229 documents, with an average annual growth rate of 13.49%, and the average number of citations per document was 29.76. The document content considered Keywords Plus (ID) 9037 and Author's Keywords (DE) 7036. The authors involved a totaled of 10,143, with 130 single-authored documents, and the number of co-authors per document was 5.24, including international collaborations. This methodology presents significant research indicators and provides valuable information on climate change adaptation research regarding its extent, cooperation, and influence. Through scientometrics, various keyword co-occurrences and thematic evolutions can be identified, illustrating how research themes have developed over time, particularly in response to the global need for sustainable solutions

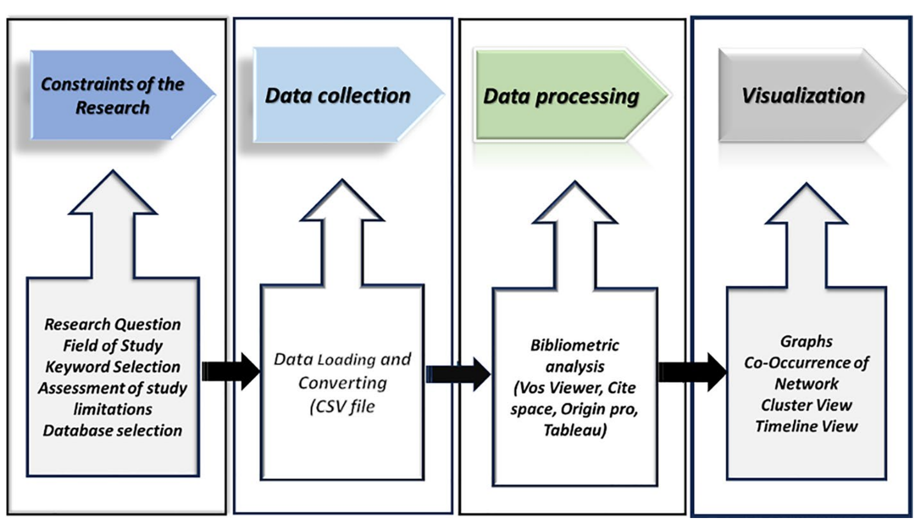
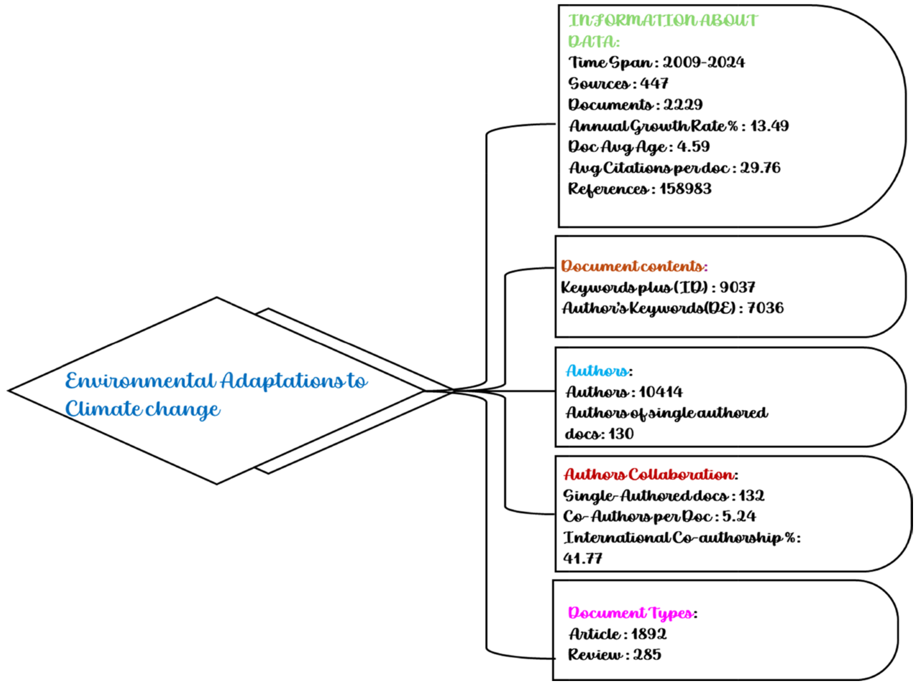


Fig. 5 A typical scientometric based research design concept

Fig. 6 Research Impact Metrics



and technological advancements. Focus areas are evident in diverse disciplines including engineering, environmental sciences, and computer science, highlighting the interconnected nature of modern research. In general, the dynamic and collaborative nature of contemporary scientific research is driven by global efforts to innovate and address complex issues. Figure 7 depicts the geographical distribution of research activities with countries such as the United States, China, India, and several European nations that prominently contribute to academic output. Network maps indicate robust international collaboration, emphasizing the connections between leading researchers and institutions.

Above mentioned figure (Fig. 8) provides an overview of the spatial distribution of research internationalization, as well as its scope. The circular bar chart details the Mean Citation Percentage (MCP) of research papers of countries of interest of "global research trends on environmental adaptation to climate change." The shaded arc for each color shows the country and its MCP marked along the arc to exemplify the mean citation effects of research in this area. We discovered that the United States (USA) has the highest MCP of 9.14%, which is represented by the inner blue arc, labelled as" high,' and this reveals a high citation impact relative to the other countries. Next, to the USA, China has MCPs of 6.33%>, followed by Australia with 6.2%> indicated in red and orange, respectively. Other top contributors include United Kingdom with MCP

Fig. 7 Multiple-country publications of authors

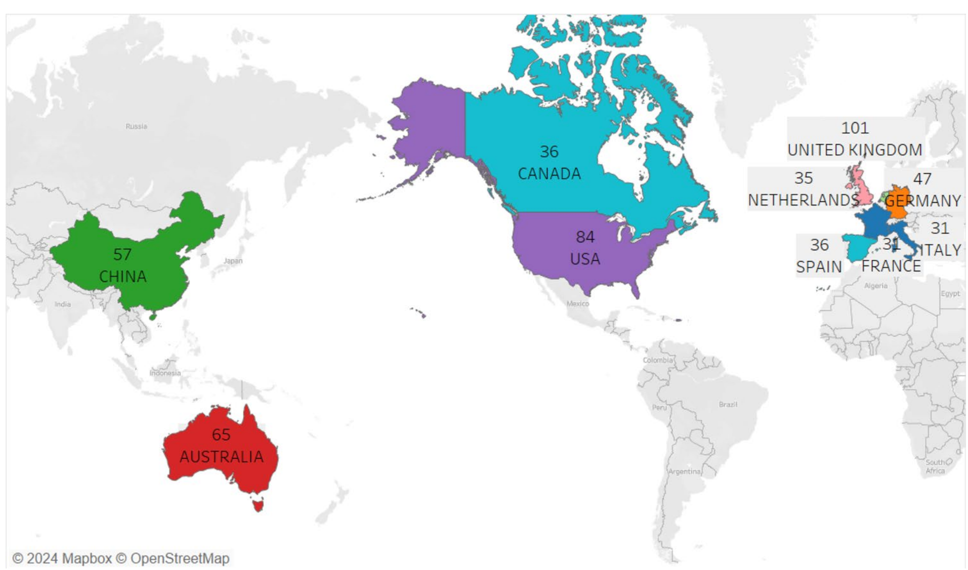
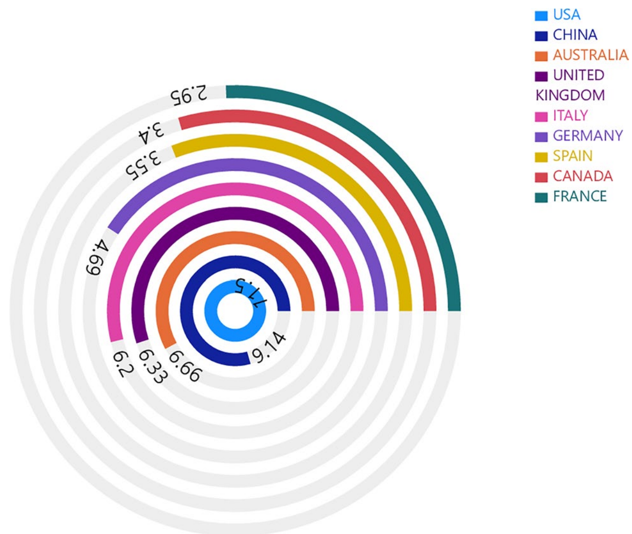


Fig. 8 MCP% of authors' countries



value of 4.69% shown in purple arc), Italy at 4.4% shown in the yellow arc), and Germany at 3.55% this is shown by the dark pink arc). The remaining countries with relatively low MCPs are Spain (3.4%), Canada (2.95%), and France (brown, pink, and green arcs, respectively). Most importantly, the circular format of the chart can easily help in a comparison of the citation impact of nations; nations with longer arcs are those with higher MCPs. In conclusion, this visualization reveals that the USA has the strongest citation impact of all nations in climate adaptation research, meaning that there is variation in the impact of research output in this crucial environmental area across nations worldwide.

Figure 9 provides an understanding of the location and temporal distribution of research activities. Thus, these research trends can be identified, sources of knowledge development can be investigated, and new tendencies or research gaps can be revealed. Each circle denotes a particular country, such as the United Kingdom, France, or China, to show that they participate in these research themes. The size of each circle is proportional to the volume or impact of the research output of each country, with larger circles indicating a greater contribution. For example, the United Kingdom and China have invested more effort in climate change studies, whereas other countries such as Norway and Italy have invested more in thermal comfort and soil, respectively. The immobilized lines and arcs show cooperation as well as a similar research focus between countries regarding how various nations play a role in increasing the global knowledge base of these subjects. It demonstrates not only the increase or decrease in research interest in these fields of study in the past several years but also the development of complex networks and collaborations that arise as these topics progress.

Figure 10 shows the trends in international cooperation and citations for countries involved in the development of research. Network nodes can correspond to countries, and the size of the nodes can reflect the number of citations, or therefore, the impact of a country's research work. Nodes such as the United States, the United Kingdom, Australia, and the Netherlands show that these countries have a high citation density, which means they contribute significantly to the field of research. The connecting lines point to cooperative links or citation relations with the nodes that reflect the countries. Thicker connections represent higher levels of cooperation or references shared between institutions and countries, whereas thin connections represent low levels of cooperation/reference. When these connections are compared, one can identify the leading countries in advancing research frontiers and the countries that are evolving to

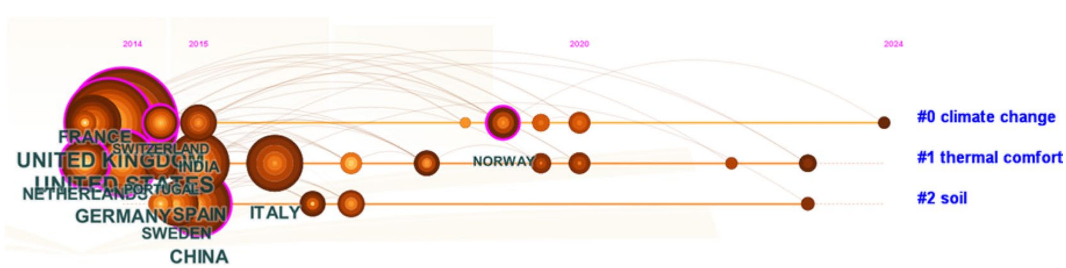


Fig. 9 Timeline view of the author country

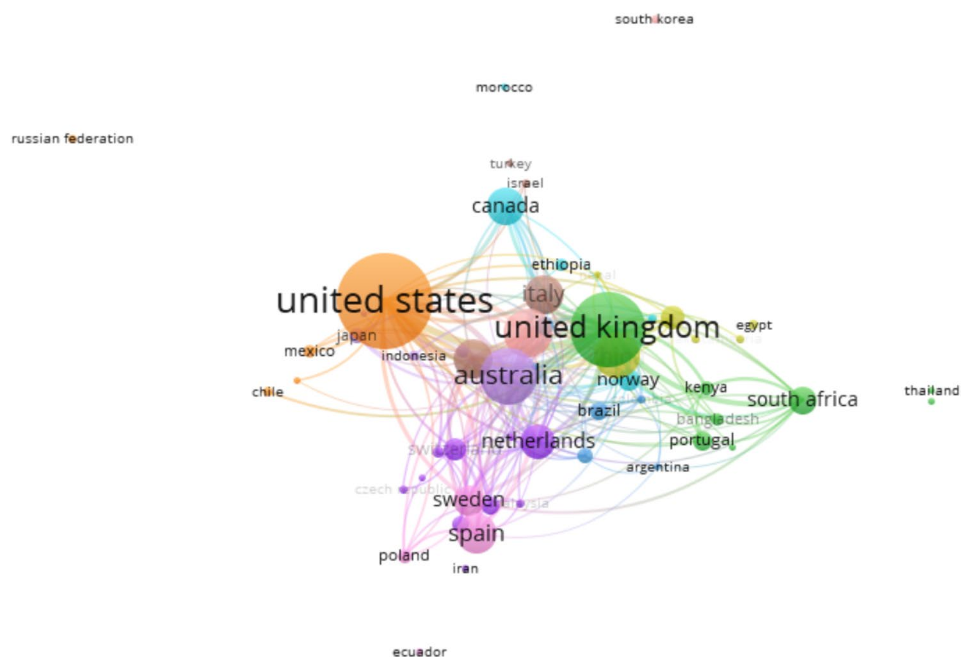


Fig. 10 Co-occurrence network of countries and citations

become significant partners. This information is useful for various stakeholders, such as researchers who are in need of partners worldwide, policymakers, and funding agencies who need to direct their resources in better ways to increase the impact of research worldwide. Knowledge of such patterns may lead to more effective collaboration, thus improving the quality of the study and the impact of the findings.

Figure 11 is a violin plot from a study on "global research trends in environmental adaptation techniques focusing on climate change," showing the distribution of three metrics: Articles, the Mean Total Citations per article (MeanTCperArt), and Citable Years. Each violin shape corresponds to the dispersion of observed data for each investment metric. The vertical axis of each plot shows the values, the box shows the interquartile range (25%–75%), and the line through the box is the median. The "Articles" metric, which has the highest application, shows that the number of publications within the studies differs vastly, meaning variable productivity among research work. "MeanTCperArt" means the number of citations per article in terms of averages, and the spread is not very broad meaning that most articles receive similar citation. The 'Citable Years' has the lowest variance, which implies that the period of time that it considered to be within the applicable citation period is highly standardized in this study. The dots represent the median of each parameter, and the straight bars (whiskers) correspond to the data distribution within 1.5 the interquartile distance. Overall, this type of visualization greatly emphasizes differences in the number of publications, citation indices, and citation half-life in the climate adaptation area.

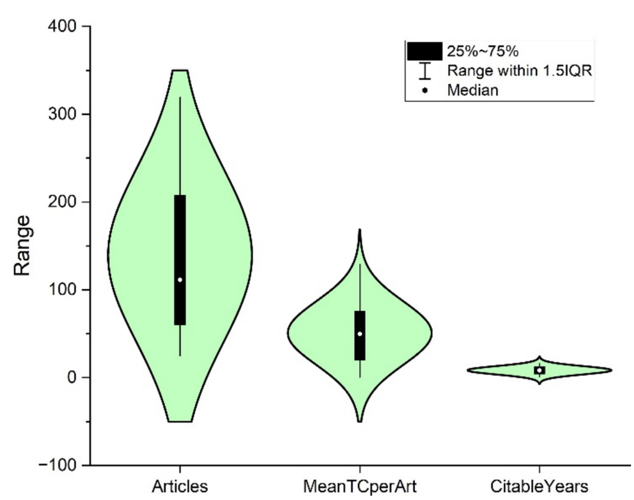


Fig. 11 Violin plot (normal distribution) of articles, mean total citations per article, citable years

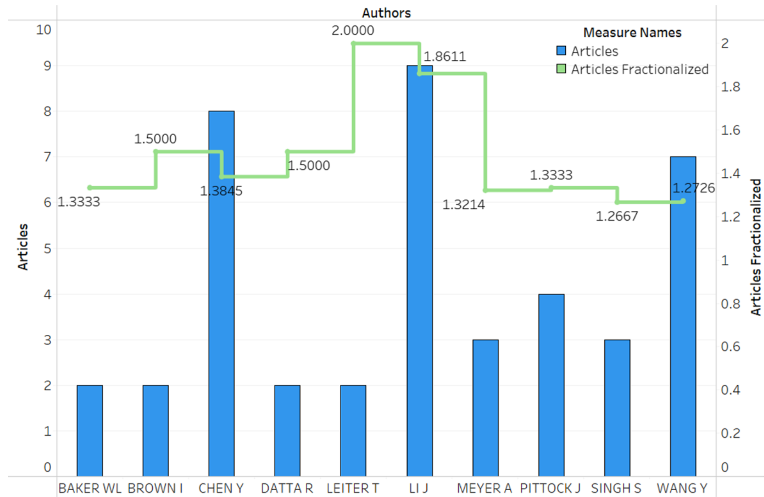


Fig. 12 Comparative analysis of articles and fractional authorship across authors

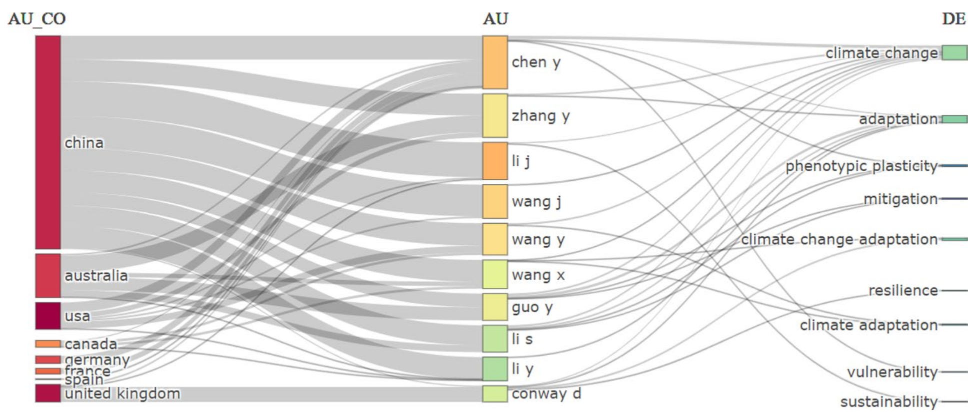


Fig. 13 Three-field plot

Figure 12 compares the research output of various authors based on two metrics: the total number of articles published (represented by blue bars) and the number of articles fractionalized (represented by the green line). Fractionalized articles consider the number of co-authors and the distribution of credit for a publication among all contributors. This method provides a more balanced view of each author's contributions, particularly in collaborative research fields. The graph shows both absolute and adjusted contributions, providing a nuanced view of each author's output. For example, while author LI J has the highest number of articles, fractionalizing the count adjusts the credit, showing a different perspective on individual contributions. This allows for a fair comparison of productivity, particularly in collaborative environments. Drawing on this graph serves several purposes: it provides a clear visual representation of the authors' research productivity, helps identify leading contributors, and helps to understand collaboration dynamics. Such insights are valuable for academic assessments, grant allocations, and understanding the impact of research. Using both raw and fractionalized counts, the graph balances the recognition of high-volume publishers with a fair distribution of credit, promoting a more accurate evaluation of scholarly contributions. This approach encourages collaboration while maintaining individual accountability in the research output.

Figure 13 shows the connectivity, share, and distribution in terms of countries, authors, and research interests, focusing on the environment and climate. It reveals the countries that publish more articles, indicates the authors who produce the most articles in these fields, and pinpoints the research areas that are of the main interest to them. The left side of this diagram provides a global overview of the main countries that have contributed greatly to this area of research, including China, Australia, the USA, Canada, Germany, France, Spain, and the UK. The size of the bars reflects the amount of research activity recorded in each country. The middle column shows the individual authors from these countries and their contributions to IJRM. These lines denote the places where these researchers are based, and show which countries are connected, thus showing collaboration by the authors. The right column provides important research topics related to climate change, adaptation, phenotypic plasticity, mitigation, resilience, and sustainability. The relationships between authors and these topics define the fields of interest of authors and show how authors from different countries contribute to climate and environmental studies. It determines the major actors in the area, encourages interorganizational cooperation, and guides choices for research appropriations and policy setting by establishing parallels between the supply and demand of human and financial capital for worldwide challenges. The thematic evolution of the keywords from 2009 to 2024 is shown in Fig. 14.

This Sankey diagram was drawn to visualize the evolution of research topics related to climate and environmental studies over three distinct time periods: Of these, the 2009–2014, 2015–2019, and 2020–2024 strategic plan and maps are important to consider. The flow and transition in the diagram depict how interest in certain research areas transitions from one phase to another. Each time period has elements on the left that show the main themes of the research, and the links show whether the research is continuous or shifting between the themes. The first period of research activities and keywords (2009–2014) included genetic adaptation, phenotypic plasticity, climate change, and bacteria as the main research focus, where the adaptations of biological organisms to environmental changes were of utmost interest. In 2015–2019, interest expanded, while climate change remained important, and researchers and practitioners added new topics such as conservation of biological diversity, conventional gardens, and migration with help. These changes indicate a shift toward proper conservation and management of species diversity. Among the priorities in the most recent 5-year period (2020–2024), there are ongoing and new priorities, namely, local adaptation, thermal comfort, nature-based solutions, and risk assessment, which show a tendency towards practical and climate-resilient solutions. This diagram is useful for researchers, policymakers, and educators as it offers information on the changes in the field and the tasks that are set in the scientific community. It helps discover trends and knowledge gaps, together with helping to decide pathways for additional research and resource distribution for the mitigation of environmental and climate issues.

The bar graph (Fig. 15a) shows how the terms 'climate change',' adaptation ', and 'ecosystem' appear in research between 2009 and 2024. Figure 15b shows a line plot to represent the probability distribution of these keywords over the following periods. The decades-2009–2013, 2014–2019, and 2020–2024. The most widely known term is the keyword 'climate change, which has been used more often than other terms and has become familiar in recent years. Other words such as 'adaptation' and 'adaptive management' are also frequently used, but not like the word 'adaptation,' which is frequently used in the literature line plot. The line graph shows how these terms have been used over time, and changes in their probability distribution may be helpful in establishing new trends and directions for the study. Thus, these visualizations are helpful in making decisions related to specific trends in the areas of interest during the years. They help scholars, policymakers, and funding agencies understand the areas they should fund by directing their resources to them. By looking at the change in keywords, scientists can map the process of the growth of what is known as scientific language and therefore reorient their work so that it becomes appropriate in the present and produces expectations of what is yet to be achieved in the future. The probability density of the words most commonly used to refer to climate and adaptation themes in each period is shown in the above graph. In this case, it is possible to state that these words, such as 'climate change' and 'adaptation,' have much higher probabilities, which could characterize their frequency in the focus of people and media during recent decades and, particularly, from 2009 to 2024. This means that the concerns have stuck with a certain range of fluctuation that has not increased or lowered them significantly, while other terms such as 'biodiversity' and 'vulnerability' are also used less, but their fluctuation is also relatively insignificant.

Table 2 displays a collection of keywords associated with environmental and climate research, arranged in two dimensions (Dimensions 1 and 2) and grouped into a single cluster (Group 1). These dimensions most likely represent coordinates from multidimensional scaling or factor analysis, where the values indicate the positioning of each keyword in a reduced-dimensional space. For instance, the keyword "Climate change" has coordinates (0.03, 0.06), while "Sustainable development" has coordinates (– 0.31, 0.89). Keywords were related, meaning that they all impacted the same topic

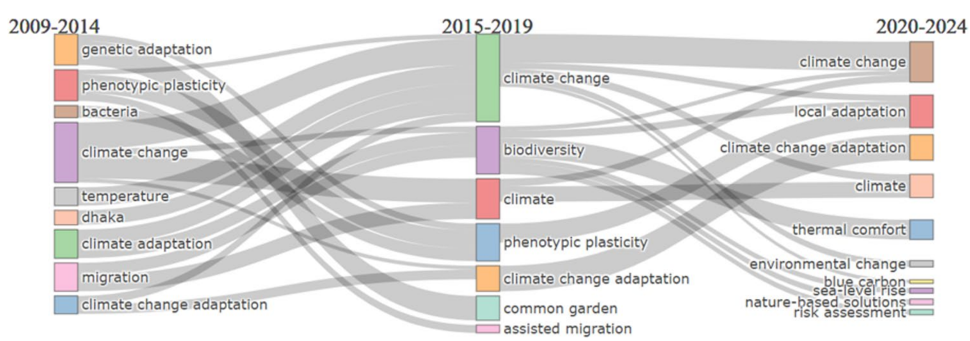
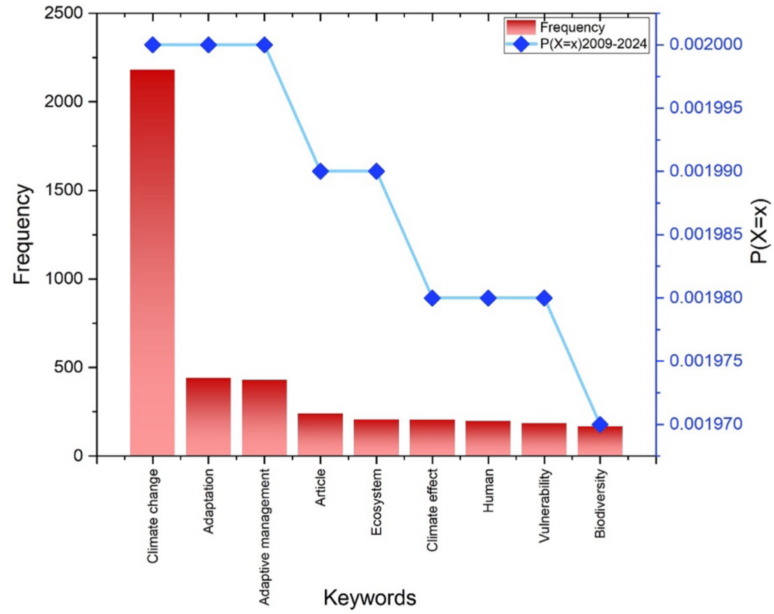
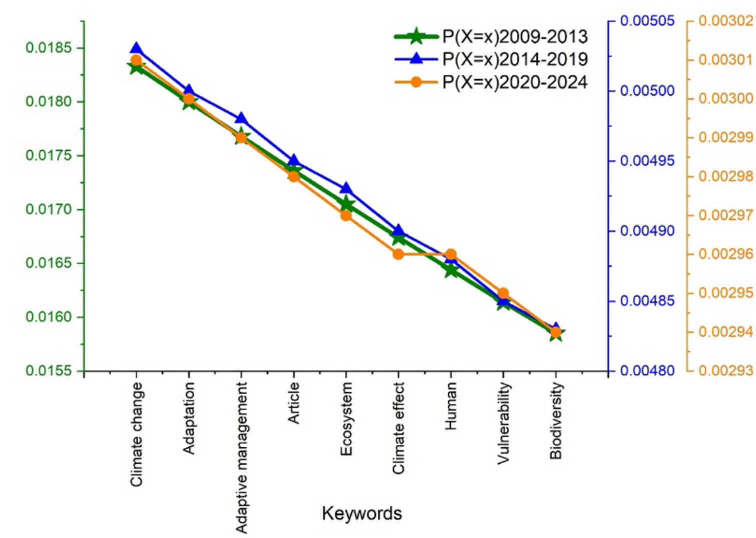


Fig. 14 Thematic evolution of keywords during specific period

Fig. 15 **a** Statistical analysis of keywords (2009–2024). **b** Statistical analysis of keywords (2009–2013, 2014–2019, 2020–2024)



(a): Statistical analysis of keywords (2009-2024)



(b): Statistical analysis of keywords (2009-2013, 2014-2019, 2020-2024)

and could be used to contribute to conversations about climate, sustainable systems, and ecosystems. Table 3 provides information related to citations and pertinent documents.

Table 2 Keywords and their dimensions

Word	Dimension 1	Dimension 2	cluster
Climate change	0.03	0.06	1
Adaptive management	− 0.23	0.41	1
adaptation	0.4	− 0.16	1
article	1.44	1.03	1
ecosystem	1.82	0.05	1
human	1.48	1.5	1
Risk assessment	− 0.17	0.63	1
temperature	1.85	− 0.78	1
Climate effect	0.29	0.32	1
biodiversity	0.2	0.28	1
vulnerability	− 0.24	0.56	1
Sustainable development	− 0.31	0.89	1
humans	1.73	1.55	1
acclimatization	1.79	− 0.63	1
sustainability	− 0.52	0.5	1

8 Conclusions

Mitigation of climate change in the environment is achieved through various measures aimed at sustaining species and ecosystems. Knowledge of genotype-by-environment interactions is important for the breeding of durable crop varieties that feed the world, especially under a changing climate. Human adaptations must be established, especially in the areas of food, energy, and water, owing to current changes in the environment that require new and efficient resource management systems. The results showed the geographic location of the authors in climate change studies, collaboration networks, and focus areas. With the use of the MCP% circular chart, this notion is further highlighted, where such countries significantly contributed to multiple country publications. The change in keyword density is visualized in a timeline view, which reveals that the research focus has changed over the years. The co-occurrence network map shows that there are close working relationships that have been magnified, especially among developed countries, indicating that their research activities are interrelated. The violin plot shows the distributions of the analysis of citation metrics for different articles, which implies that the impacts of research are different. A table is constructed that provides a mix of articles with high and low citation indices; hence, it is concluded that, although some publications have global reach, others remain confined to the regional context. Citation ratios confirm that there are informative and conclusive documents within their spheres of interest.

Climate change is becoming a pressing issue that demands immediate attention, but it also calls for proactive management of the adaptive capacity of the biosphere, which is changing quickly. However, these adjustments pose a serious threat to the management and conservation of natural resources. Therefore, it is imperative to investigate forward-thinking conservation techniques to promote resilience and adaptation. This is especially significant because there is an urgent need to address human impacts on Earth's climate system. It is also critical to implement conservation measures that will allow species to adapt, encourage ecosystem resilience, and preserve interconnected human-ecological systems that sustain humankind. In conclusion, forest and ecosystem management strategies aim to increase the level of resilience, reduce carbon emissions, and preserve biological diversity as critical factors for ecosystem stability. Subsequent research should focus on the potential to scale up effective adaptation initiatives and their socioeconomic consequences, with the aim of developing a more inclusive global framework for adaptation.

Table 3 Local and international document citations

Document	DOI	Year	Local citations	Global citations	Ratio
CAPBLANCQ T, 2020, ANN REV ECOL EVOL SYST	https://doi.org/10.1146/annurev-ecolsys-020720-042553	2020	6	138	4.34
NIGHTINGALE AJ, 2020, CLIM DEV	https://doi.org/10.1080/17565529.2019.1624495	2020	5	276	1.81
NELSON LK, 2022, MARIT STUD	https://doi.org/10.1007/s40152-021-00252-z	2022	2	9	22.22
JOHNSON LC, 2022, J ECOL	https://doi.org/10.1111/1365-2745.13695	2022	2	34	5.88
WANG F, 2021, TREES STRUCT FUNCT	https://doi.org/10.1007/s00468-020-02011-9	2021	2	23	8.69
EVERTSEN KF, 2020, CLIM DEV	https://doi.org/10.1080/17565529.2019.1596059	2020	2	42	4.76
KROEKER KJ, 2020, GLOBAL CHANGE BIOL	https://doi.org/10.1111/gcb.14868	2020	2	93	2.15
ESTRELA-SEGRELLES C, 2023, WATER RESOUR MANAGE	https://doi.org/10.1007/s11269-023-03469-1	2023	1	6	16.66
JACQUEMONT J, 2022, ONE EARTH	https://doi.org/10.1016/j.oneear.2022.09.002	2022	1	47	2.12

Author contributions G.S.—Table creation, Prepared figure. R.G.—Conceptualization, final check. B.H—Ideology, Manuscript drafting. D.A.—Manuscript Drafting, software output. S.S.—Organizing and validation. S.V.—Final check.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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