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REVIEW

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Climate change and plant–pollinator interactions: global research trends and visualization

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Background: The mutualistic interactions between plants-pollinator is one of the most significant fields of research in ecology, which gives information on the biotic network architecture, coexistence, diversification, and ecosystem function. In this study, our research intends to identify the literature production rate, global collaborations, research hotspots, and trends in research addressing the influence of climate change on the relationship between plants and pollinators.
Results: Research and review papers on climate change and their impact on plant-pollinator interactions published in the Scopus database were retrieved. The contributions of nations, journals, institutions, current trends, and keyword analysis were shown using VOSviewer and R-Studio bibliometrix to produce a network map of author collaboration across nations. The Scopus database (2007 to 2023) generated a total of 256 entries, out of which 229 publications were examined after the screening procedure. As per our data analysis, *The Rocky Mountain Biological Laboratory* and *Journal of Ecology* were the most productive organization, and journal, respectively. The author with the most publications was *Laura A. Burkle* of *Montana State University*. The *United States* is ranked first among all nations in terms of the global literature production on the effects of climate change on interactions between plants and pollinators. As per our analysis, we identified four primary research areas (1. climate change and temporal mismatch in plant-pollinator interactions, 2. climate change and impacts on pollination networks, 3. adaptations under abiotic stress, 4. climate change effect on pollinator behavior) through the analysis of keywords.
Conclusions: This study highlights current research status on the effects of climate change on plant-pollinator relationships and is an early attempt to understand how these connections form and alter.

Keywords: climate change, diversity, plant-pollinators interaction, reproductive ecology

Introduction

Ecological interactions are a crucial component in maintaining the diversity of life on Earth. Mutualistic interactions between species exists in every ecosystem, and plant-pollinator interactions are excellent examples of mutualism (Kawata and Takimoto 2023; St-Onge et al. 2022). Global concern for pollinators is escalating due to the increasing crisis, with indications that climate change will intensify population decline, affecting ecosystem resilience and food security both locally and globally (Marshman et al. 2019). The Global Pollinator Assessment (IPBES 2016) showed a significant decline in the wild pollinators population in the North Temperate Zone, while extensive recent research in Western Europe demonstrated severe reductions in pollinator biodiversity and biomass across various taxonomic categories (Potts et al. 2016). Approximately 85% of angiosperm plant species and 33% of the world's cultivated crops are pollinated by animals, with insect being the dominant contributors (Burkle et al. 2013; Buxton et al. 2022; Potts et al. 2016). Despite the critical role of insect pollinators in facilitating ecosystem services for approximately 80% of flowering plants, their population have experienced a sharp decline of 20%–40% increasing the concern of ecologists all over the world (Nath et al. 2023). Habitat loss, pollution, pests and pathogens, climate change and use of pesticides are the listed drivers of pollinator decline, with climate change being the significant factor contributing to the population decline (Brunet and Fragoso 2024). Recently, Singh et al. (2024a) assessed the current status and future of habitat suitability for Himalayan bumblebees using species distribution model. According to their report the habitat conditions in the Himalaya are not favorable for bumblebees and only 15% of the Himalayan region is suitable. Therefore, this region should be considered a priority area for their conservation (Singh et al. 2024a). Water and temperature stress limits the quantity of pollen and nectar production affecting the plant-pollinators interactions (Descamps et al. 2021; Gallagher and Campbell 2017; Waser and Price 2016). Higher temperature increases the mortality rate in larvae causing the reduction in pollinator diversity (da Silva et al. 2017; Ostap-Chec et al. 2012).

Response diversity refers to the variety of responses by species within functional groups to environmental change which is crucial for the resilience of ecosystem (Elmqvist et al. 2003). In plant-pollinator interaction where differences in phenological shift rates are seen across several species within the same group. Because of this, mismatches occur between interacting species when the phenological overlap between them decreases (Cook et al. 2012; Primack et al. 2009). Despite the fact that precipitation also profoundly influences phenology by regulating soil moisture, it is thought that temperature is the primary factor causing the shift in phenological events. Examples of such phenological mismatches may be found in a wide range of biological systems, mainly in temperate and arctic locations (Kudo and Ida 2013; Post and Forchhammer 2008; Yin et al. 2023). With the exception of a few isolated instances when plants and pollinators interact negatively, generalist plants and insect pollinators demonstrate generally similar rates of phenological progress in response to global warming because of their adaptable relationships (Bartomeus et al. 2011; Burkle et al. 2013; Ovaskainen et al. 2013). Because the plants that are the only source of food for herbivores in alpine locations are impacted by early or late flowering phenology changes, it eventually affects how they forage. In many cases, herbivores seem to be adapting to climate change more quickly than their host plants, which has modified the selection pressure and created unusual ecological connections in their new environments (de Sassi and Tylianakis 2012; Hamann et al. 2021; Lu et al. 2013). Few experiments have shown that 17%–50% of pollinators were affected due to disruption in food supply and temporal mismatches, leading to changes in pollinator demography (Memmott et al. 2007; Ren et al. 2020).

Bibliometric analysis refers to the quantitative and qualitative evaluation of the published literature in a particular research area by using mathematical and statistical tools. Bibliometric analysis is a useful technique for providing an overview of national and global contributions of the available literature in a specific field and finding research gaps that may be addressed in future studies (Ellegaard and Wallin 2015). Throughout recent years, various examinations have led bibliometric researches in different scholarly subjects (Belter 2015; Singh et al. 2023). Rather than comprehensive reviews, which endeavor to dissect a specific examination issue in a few sets of publications, bibliometric analysis provides a comprehensive assessment of the writing in a specific region (Møller and Myles 2016). This study intends to gain insight into the research trends on climate change's impact on plant-pollinator interactions and provide references for future research by examining the worldwide correlations between the research trends and hotspots in this field. In addition, policymakers and funding organizations can decide where to allocate resources by obtaining information about current research trends and hotspots in the field. These contributions are framed as a series of questions, as follows:

Question 1: *What is the global publication trend?*
Question 2: *Which countries, institutions and authors exerted the greatest influence and demonstrated the highest level of productivity in the advancement of climate change and plant-pollinators interaction?*
Question 3: *Which journals, and publications have made the greatest contributions to research based on climate change and plant-pollinators interaction?*
Question 4: *What are the research trends and the current emerging topics in climate change and plant-pollinators interaction domain?*

Materials and Methods

Data source and search strategy

Articles were retrieved from the Scopus database and assessed both quantitatively and qualitative, as included in bibliometric analysis (Singh et al. 2024b; van Raan 2014). The search was conducted in a single day, to remove the errors due to additions in the database. Scopus search was performed on 1st September 2023, using search strategy (TITLE-ABS-KEY ("*plant-pollinator interactions*") AND TITLE-ABS-KEY ("*climate change*") OR TITLE-. -KEY ("*global change*") OR TITLE-ABS-KEY ("*global warming*") as a result, a total of 256 published documents were retrieved.

Data analysis software packages

The retrieved data was downloaded in comma-separated value (CSV) format and transferred to MS Excel for tabulation and further analysis. The data was also exported to VOSviewer version 1.6.19.0. (https://www.vosviewer.com) software and bibliometrix R-package (http://www.bibliometrix.org/) for mapping and visualization of the networks. The node size represents the frequency of articles, and the thickness of connecting lines indicates the link strength in VOSviewer networks. Information such as global literature publications, most relevant authors, international collaborations, and trend topics was obtained through the bibliometrix R-package. Co-occurrence, co-authorship and co-citation networks was obtained by using VOSviewer bibliometrix R-package (Aria and Cuccurullo 2017; Mohammed and Li 2023; van Eck and Waltman 2010).

Data screening was performed based on multiple criteria including year of publication, language, and document type. Inclusion criteria for this bibliometric study were restricted to research articles published in the English language between 2007–2023. Publications such as book chapters, conference papers, and editorial letters, as well as work published before 2007, were excluded from the analysis. A total of 229 publications were identified for bibliometric analysis. PRISMA flow diagram illustrating the data selection process and search strategy is shown in Figure 1.

Results

Annual publication trend

After screening, 229 publications related to the impact of climate change on plant-pollinator interactions (ICCPI) were included, out of which 199 were articles and 30 were reviews. Figure 2A shows the number of yearly publications on ICCPI from January 2007 to July 2023. Although the number of publications on this topic was consistently low over the first few years (2007–2011), Figure 2A shows that from 2015 to 2022, there was a continuous growth in the volume of literature (14.31%), signaling the beginning of, interest in this field of study. The literature output growth curve was linear, and the equation used to fit the curve was $y = 1.5015x + 1.55$; $R^2 = 0.7475$, predicting an increase in the number of publications on ICCPI in the next years.

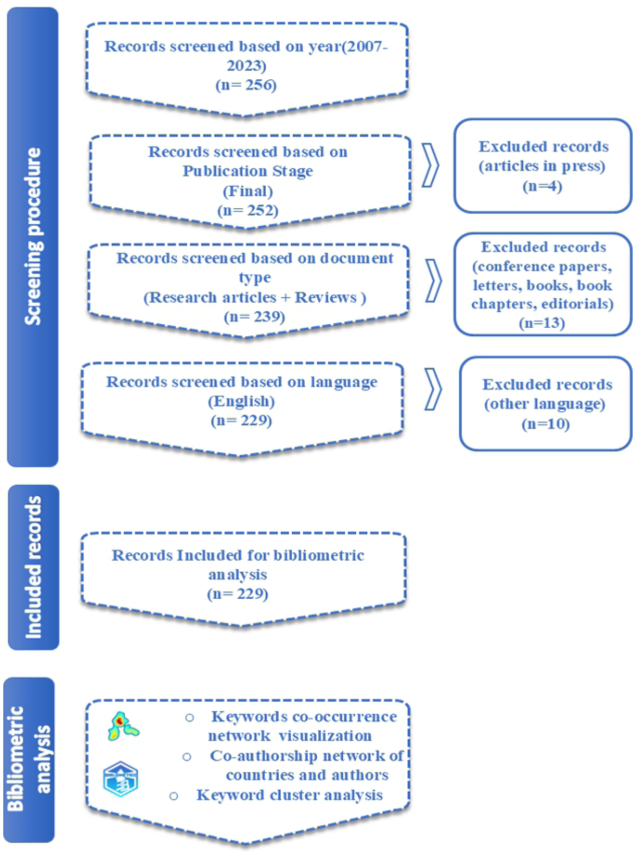


Fig. 1 The flow diagram of the screening of literature dataset.

Top 10 journals and institutions

A total of 229 articles were published in 103 well-known journals all across the world (Table 1). Approximately 36% of publications on ICCPI are attributed to the top 10 journals. "*Journal of Ecology*" published by British Ecological Society, Wiley-Blackwell, ranked first with 11 publications and 363 citations. Both "*American Journal of Botany*", and "*Ecology and Global Change*" each with 10 publications ranked second in this field followed by "*Ecology Letters*" with eight publications. The impact factors of publishing journals range between 11.6 to 2.6 as per the Journal Citation Report 2023. The journal "*Ecology Letters*" has the maximum citation (n = 2,181), followed by "*Science*" (n = 718) and "*Ecology*" (n = 695) (Table 1). The authors who participated in the ICCPI study represented 160 institutions, and Figure 2B highlights the institutions with the highest number of published works. "*Rocky Mountain Biological Laboratory*" (n = 19), "*CNRS Center National de la Recherché Scientifique*" (n = 12), "*University of Arizona*" (n = 10), "*University of Maryland*" (n = 11), and "*Montana State University*" (n = 40) were the organizations that publish the most publications (Table 2).

Top countries and their cooperation

Co-authorship analysis of nations investigates collaboration among researchers, which can lead to improvements in the clarity and insight of a certain research topic (Klarin 2024). A total of 47 countries has contributed to research related to ICCPI. "*U.S.A*" was the most productive country with maximum number of published documents (n = 85), followed by "*Germany*" (n = 41), "*United Kingdom*" (n = 21), "*Canada*" (n = 17) and "*France*" (n = 16). The output indicated that these countries have the maximum investment and funding for the research in this field resulting in strong research strength by the countries (Fig. 3A). Figure 3B represents the international cooperation in publishing literature with the threshold of five documents per countries. In the network visualization it is clearly observed that "*U.S.A*" has the maximum number of collaboration (n = 41) among the countries followed by "*Germany*" (n = 40) and "*United Kingdom*" (n = 22).

Top author and author's co-citation analysis

A total of 751 authors were involved in ICCPI research,

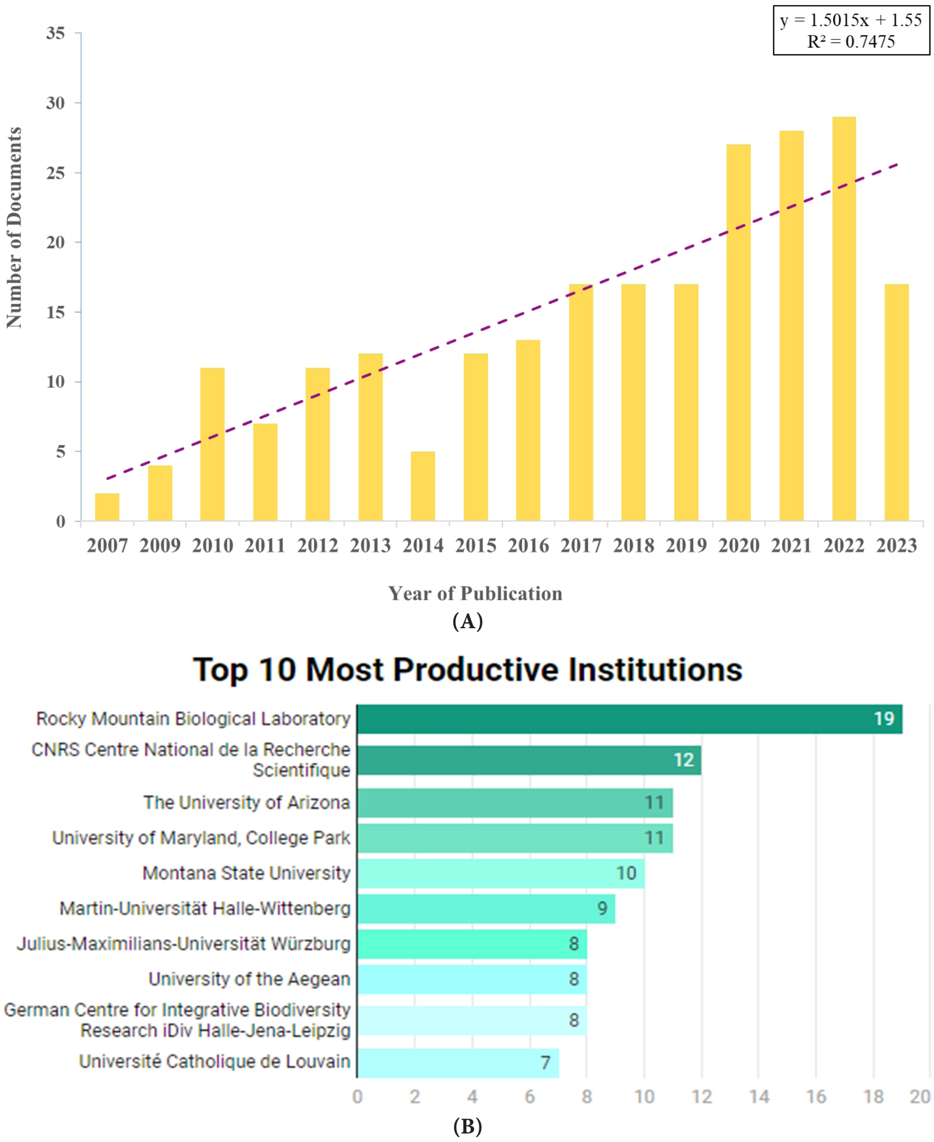


Fig. 2 (A) Annual publications on impact of climate change on plant-pollinators interactions, (B) Top 10 most productive institutions.

Table 1 Top 10 most productive journals

S. No.	Journals	IF	Articles	Total citations
1	Journal of Ecology	5.5	11	363
2	American Journal of Botany	3	10	513
3	Ecology	4.8	10	695
4	Global Change Biology	11.6	10	422
5	Ecology Letters	8.8	8	2,181
6	Proceedings of The Royal Society B: Biological Sciences	5.53	8	145
7	Functional Ecology	5.2	7	234
8	Oikos	3.4	7	578
9	Ecology and Evolution	2.6	6	129
10	Frontiers in Ecology and Evolution	3	6	15

As per JCR report 2023.
IF: impact factor; JCR: Journal Citation Report.

and the author who published the most publications (n = 11) was "Laura A Burkle" from "*Montana State University*", followed by "David W. Inouye" from "*University of Maryland*" (n = 10), and "Rafferty NE" from "*University of California*" (n = 9) (Table 2). Each of the top 10 most cited authors has received more than 5,000 citations overall, with more than 25 citations per article on average. Co-citation is a method for determining how frequently two writers were cited together in other works. In this co-citation analysis, 135 authors out of 2190 had at least 35 citations, which

Table 2 Top 10 most productive author and their co-citation analysis

S. No.	Authors	Affiliation	Articles	Citations	Average citation per document	h-index
1	Burkle LA	Montana State University, United States	11	1,341	121.90	26
2	Inouye DW	University of Maryland, College Park, United States	10	530	53	49
3	Rafferty NE	University of California, Riverside, United States	9	527	58.55	14
4	Irwin RE	NC State University, United States	7	339	48.42	46
5	Jacquemart A-L	Université Catholique de Louvain, Belgium	7	196	28	30
6	Petanidou T	University of the Aegean, Greece	7	593	84.71	44
7	Descamps C	Université Catholique de Louvain, Belgium	6	165	27.5	9
8	Quinet M	Université Catholique- de Louvain, Belgium	6	165	27.5	28
9	Forrest JRK	University of Ottawa, Canada	5	506	101.2	21
10	Knight TM	Martin-Universität Halle-Wittenberg, Germany	5	766	153.2	45

As per JCR report 2023.
JCR: Journal Citation Report.

served as the threshold. In Figure 3C, the line thickness represents the strength of the co-citations between authors, and the nodes represent the total number of citations. Four distinct groups were formed from the co-cited authors. The most cited authors are Inouye DW (*n* = 331), Waser NM (*n* = 288), Bascompte J (*n* = 213), Potts SG (*n* = 205), and Steffan-Dewenter I (*n* = 192). The centrality of their nodes demonstrates the importance of their work in the field of ICCPI (Table 2).

Keywords analysis

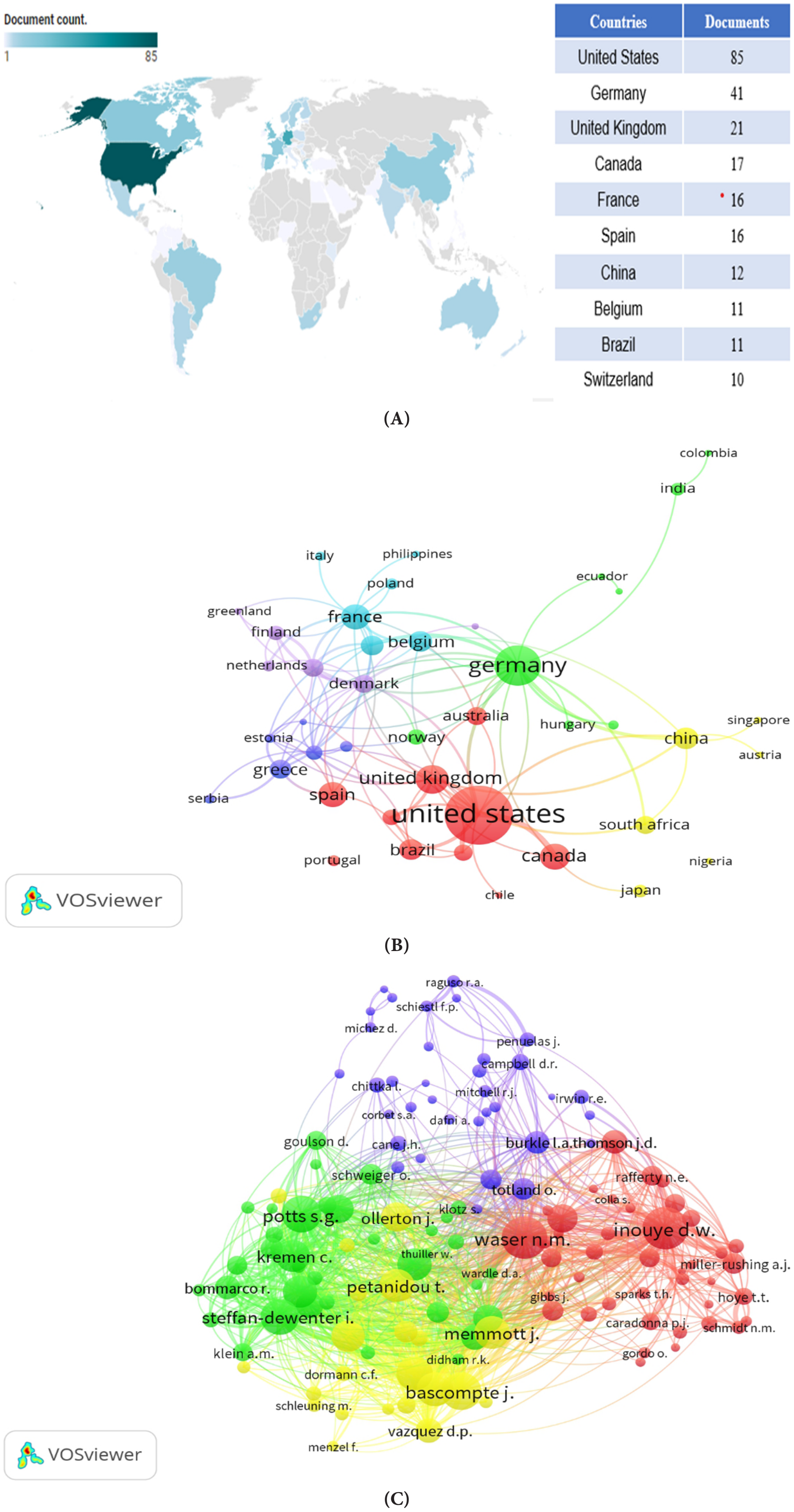
For the keyword analysis we used VOSviewer software, co-occurrence analysis of keywords is a bibliometric technique that visualize relationships among the terms frequently used in literature. The size of each node in the network corresponds to the frequency while clusters are distinguished by different colors, illustrating major thematic areas within the research filed on the impact of climate change on plant–pollinator interactions (Fig. 4A). Co-occurrence of keywords map was made using a list of 820 author's keywords. Out of all the terms used by the authors, 58 fulfilled the minimal threshold frequency and were included in the keyword co-occurrence analysis. The threshold was set at greater than or equal to three occurrences in the articles. The keywords such as "*climate-change*" (*n* = 83), "*pollination*" (*n* = 53), "*phenology*" (*n* = 40) "*plant-pollinator interactions*" (*n* = 20), and "*global change*" (*n* = 16) occurred with maximum frequency. Overall, four distinct clusters were discovered, reflecting four distinct research trajectories. Cluster 1 (de Zwaan et al. 2022) comprises total 33 keywords such as "*climate change*" "*pollination*", "*phenology*", "*plant-pollinators interactions*", "*global change*", "*flowering phenology*", and "*pollinators*". This research theme focuses on how climate change causes temporal mismatches due to shifts in timing of biological events related to plants and pollinators which is potentially responsible for reduction in reproductive success.

Cluster 2 (green) this cluster comprises 9 keywords such as "*global warming*", "*temperature*", "*plant reproduction*", "*pollination services*", "*precipitation*", and "*Bombus*". This research theme explores how climate change alters the complexity and function of pollination networks and mutualistic relationships. Cluster 3 (yellow) contains 9 keywords representing research based on influence of abiotic stress such as droughts on the physiology, behavior and interaction of plants and animals. This cluster includes keywords like "*drought*", "*nectar*", "*plant–pollinators interaction*", "*pollen*", "*water stress*", "*abiotic stress*", and "*floral rewards*". Cluster 4 (blue) has a total of 7 keywords representing study alternation in pollinator behavior and pollination efficiency induced due to climate change. This cluster consists of keywords such as "*phenological mismatch*", "*flowering*", "*biotic interactions*", "*competition*", "*ecological network*", "*fruit production*", "*phenological shift*" and "*flowering time*".

When examining the time-overlapping network analysis shown in Figure 4B, where the node colors are determined by the average time of each keyword's occurrence year. The yearly evolution of research keywords demonstrates a clear shift in the focus of studies on the impact of climate change on plant pollinator interactions. While the foundational themes such as climate change, pollination and phenology have remained consistently important. In recent years there has been a marked shift toward more specific topics such as drought, water stress, floral signals, nectar and pollen have emerged. This trend highlights the increasing focus on the consequences and mechanism of acute abiotic stressors.

Top 15 most cited research articles

The top 15 highly cited articles provide critical insight into the field's development. These influential works, spanning from 2007 to 2017, out of 15 top-cited research articles, the journal "*Ecology Letters*" published the maximum number of publications (Table 3). Most of these articles (*n* = 9) were published after 2010. The most cited article was written by Memmott et al. (2007) published in "*Ecology Letters*" with 889 citations titled "*Global warming and the*



Countries	Documents
United States	85
Germany	41
United Kingdom	21
Canada	17
France	16
Spain	16
China	12
Belgium	11
Brazil	11
Switzerland	10

Fig. 3 (A) Top 10 most productive countries with number of published documents. (B) Network of collaborations between the countries. (C) Network visualization of co-cited authors.

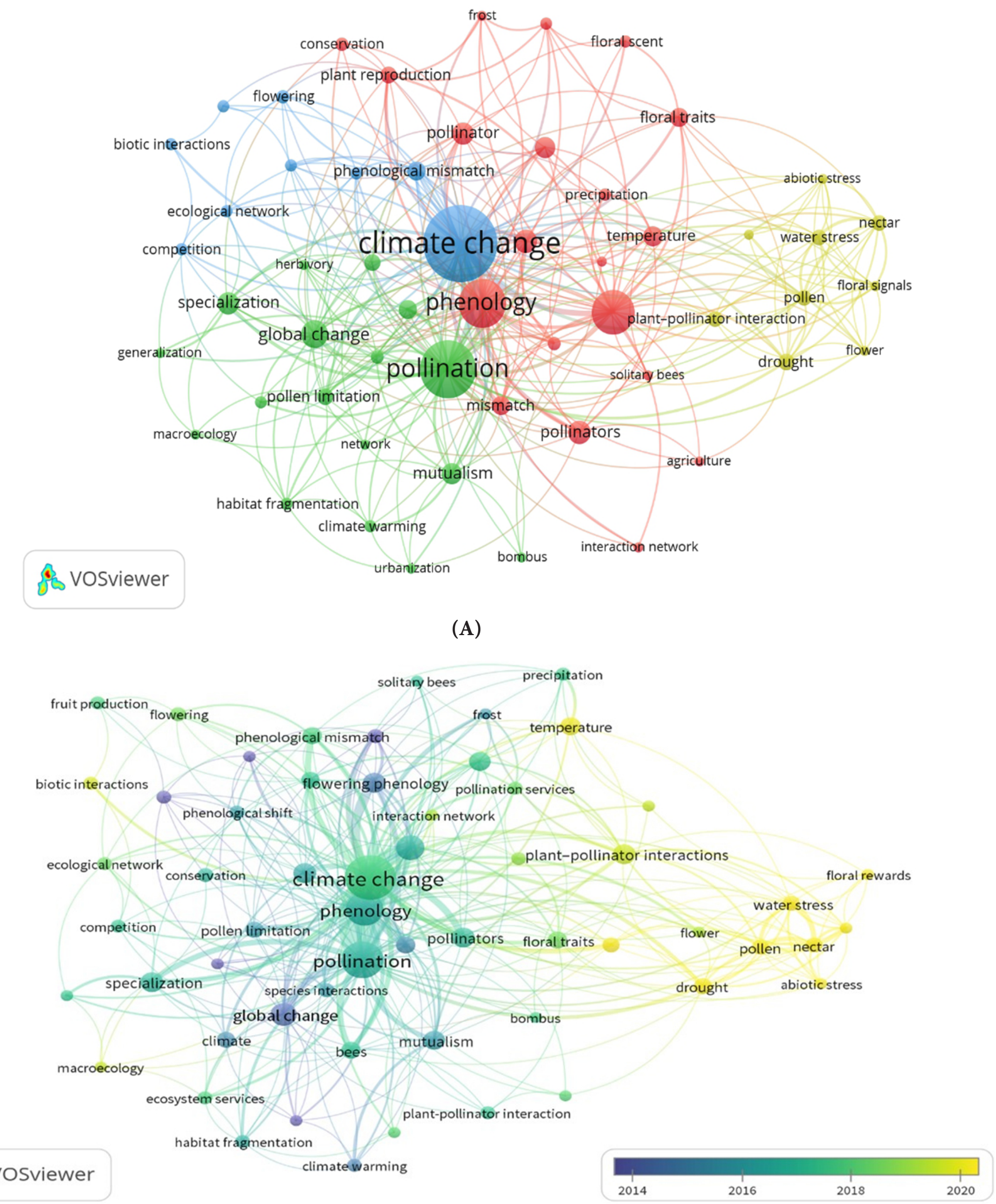


Fig. 4 (A) Visualization of the co-occurrence network of research keywords related to climate change and plant-pollinator interactions. (B) Overlay network visualization showing the temporal evolution of research keywords.

disruption of plant-pollinator interactions". The authors mimicked the effects of the phenological alterations that can be anticipated with a doubling of atmospheric CO_2 by using an empirical network of interactions between plants and pollinator species. The review article by Hegland and co-workers titled "*How does climate warming affect plant-pollinator interactions*?" was ranked second with 738 citations and also published in the journal "*Ecology Letters*". They reviewed the direct and indirect effects of climate warming on plant-pollinator dynamics. Their findings reveal that increased temperatures advance or delay phonological events resulting in temporal mismatches, which ultimately cause alterations in the distribution and abundance of species (Hegland et al. 2009).

The third most cited paper with 718 citations was "*Plant-pollinator interactions over 120 years: Loss of species, co-occurrence, and function*". In this research paper authors analyzed plant pollinators interactions over 120 years in Illinois temperate forest understory by comparing historical data from the 1800s with 2009–2010 data about 50% species loss in bee species diversity, changes in network structure, a significant decline in pollination services due to phenological shifts were observed (Burkle et al. 2013). The review titled "*Multiple stressors on biotic interactions: How climate change and alien species interact to affect pollination*" ranked fourth with 263 citations. The authors con-

Table 3 Top 15 most cited publications

S. No.	Title	Journal	Year of publication	Total citations	References
1	Global warming and the disruption of plant-pollinator interactions	Ecology Letters	2007	889	(Memmott et al. 2007)
2	How does climate warming affect plant-pollinator interactions?	Ecology Letters	2009	738	(Hegland et al. 2009)
3	Plant-pollinator interactions over 120 years: Loss of species, co-occurrence, and function	Science	2013	718	(Burkle et al. 2013)
4	Multiple stressors on biotic interactions: How climate change and alien species interact to affect pollination	Biological Reviews	2010	263	(Schweiger et al. 2010)
5	Winter climate change: A critical factor for temperate vegetation performance	Ecology	2010	262	(Kreyling 2010)
6	Artificial light at night as a new threat to pollination	Nature	2017	253	(Knop et al. 2017)
7	The future of plant-pollinator diversity: Understanding interaction networks across time, space, and global change	American Journal of Botany	2011	242	(Burkle and Alarcón, 2011)
8	Early onset of spring increases the phenological mismatch between plants and pollinators	Ecology	2013	222	(Kudo and Ida 2013)
9	Meta-analysis of phenotypic selection on flowering phenology suggests that early flowering plants are favoured	Ecology Letters	2011	219	(Munguía-Rosas et al. 2011)
10	An examination of synchrony between insect emergence and flowering in Rocky Mountain meadows	Ecological Monographs	2011	192	(Forrest and Thomson 2011)
11	Effects of experimental shifts in flowering phenology on plant-pollinator interactions	Ecology Letters	2011	170	(Rafferty and Ives 2011)
12	Urban drivers of plant-pollinator interactions	Functional Ecology	2015	166	(Harrison and Winfree 2015)
13	Plant-pollinator interactions and phenological change: What can we learn about climate impacts from experiments and observations?	Oikos	2015	163	(Forrest 2015)
14	Spatio-temporal variation in the structure of pollination networks	Oikos	2009	157	(Dupont et al. 2009)
15	Ecology and evolution of plant-pollinator interactions	Annals of Botany	2009	143	(Mitchell et al. 2009)

As per JCR report 2023.
JCR: Journal Citation Report.

ducted a comprehensive literature review of the combined impact of climate change and invasive species on plant-pollinator interaction (Schweiger et al. 2010). "*Winter climate change: A critical factor for temperate vegetation performance*" is ranked fifth in the top cited literature with a total of 262 citations. The review highlighted how snow cover reduction due to winter climate change is having a major impact on temperate vegetation. As a result of altered winter conditions, temperate vegetation is experiencing changes in species range, phenology, frost damage and disrupted plant-pollinator interactions (Kreyling 2010).

Discussion

This study was conducted to identify the hotspots and emerging trends in the field of climate change and their impact on the relationship between plants and pollinators (ICCPI). Utilizing the Scopus database, 229 articles published between 2007–2023 were analyzed using two statistical tools. The growth or decline in publishing of any study domain is recognized as a trustworthy indicator of broader trends. In every field, the quantity of publications is seen as a reliable predictor of evolving trends (Peng et al. 2020). Our study revealed limited publications prior to 2013, followed by a steady increase publications in 2015; the number of publications increased by around 12 each year. The total number of articles has increased consistently at an average rate of 14.31%, indicating a significant expansion of this field's study. The total published literature covers 47 countries/regions and more than 64% of all papers on the impact of climate on plant-pollinator interactions are from the top three nations or regions, indicating a high concentration of publications in this field of study.

The research on ICCPI involved 751 authors and 160 institutions, demonstrating that scientists worldwide are interested in how climate change may affect relationships between plant pollinators. Four out of ten top institutions are solely located in the United States, demonstrating that American academics are more concerned with how climate change may affect the mutualistic relationships between plants and pollinators in terms of total publications and citations. The United States also held the top spot, surpassing other nations. The USA was ranked first in terms of international collaboration, working with 25 other nations. The United States, Germany, and the United Kingdom were among the majority of international partnerships. It was mainly made feasible by the fact that these nations were able to attract researchers and academics from all over the world and provide them with access to funding for their work, as well as the necessary infrastructure to carry it out. The keyword analysis offered a distinct viewpoint on the growth and development of this field. By focusing on the articles, keyword analysis is used to investigate how difficulties related to an area of study relate to one another both now and in the future (Donthu et al. 2021).

Four main investigation themes, which may be grouped into different perception tactics and outcomes of shifts in the phenology of both plants and pollinators were identified in our review's keyword assessment. Cluster 1 may ultimately see a simultaneous drop in the population abundance of both plants and pollinators due to the disruption and long-term impacts of global warming, such as the mismatch of phenological synchrony between plants and pollinators (Alzate-Marin et al. 2021; Handley and Tronstad 2023; Villagomez et al. 2021; Zamora-Gutierrez et al. 2021; Zoller et al. 2023). In cluster 2, researchers investigated pollination networks to see how their community might be affected by a disturbance (Doré et al. 2021; Dupont et al. 2009; Elle et al. 2012; Minachilis et al. 2020; Pelayo et al. 2021; Santamaría et al. 2018; Xiao et al. 2017). Many researchers examined the effects of the climatic component "Drought" in cluster 3, where authors tried to scale the impacts of abiotic factors such as water stress on the plants and pollinators individually or collectively (Aldridge et al. 2011; Chakraborty et al. 2022; Gambel and Holway 2023; Hilário et al. 2023; Höfer et al. 2023; Thuma et al. 2023). Studies in cluster 4 explore alternation in pollinator behavior and pollination efficiency induced due to climate change (Hemberger et al. 2023; Olsen et al. 2022; Plos et al. 2023; Rafferty et al. 2020; Sutton et al. 2018). Variations in how plant and pollinator species adjust their phenological timing—such as earlier flowering or insect emergence—can buffer or exacerbate mismatches, influencing pollination success and ecosystem resilience. The highly cited articles collectively underscore the multifaceted effect of climate change on plant-pollinator interactions. The prominent studies (Memmott et al. 2007; Hegland et al. 2009) highlighted the early recognition of disruptions to phenological synchrony due to global warming and its further effects on pollination networks. Moreover, articles (Knop et al. 2017; Schweiger et al. 2010) published in Biological Reviews and Nature journal expand the research domain with the identification of novel stressors like artificial light and introduction of invasive species which amplify the impact of climate change. These findings have been foundational in shaping subsequent research, accentuating the vulnerability of mutualistic relationships to climate induced shifts.

Conclusions

In this bibliometric analysis, we evaluated the publications productivity and contributions of countries, authors, and journals. Our study demonstrates that annual publications, ICCPI is a rapidly growing research field driven by increasing concern about climate change ecological consequences. The maximum number of articles (n = 29) was published in 2022 and the USA ranked first in both global literature production (n = 85), and in international collaborations (n = 41) reflecting their academic and collaborative efforts. Cluster keyword co-occurrence network analysis identified a total of four distinct study fields; from phenological mismatches and pollination network disruptions to drought impacts and behavioral changes in pollinators these research areas are connected because of the diverse impacts of climate change on the interactions between plants and pollinators. The study related to understanding how climate change affects plant-pollinator interactions, including factors driving variation, species resilience, and mismatches at the species level; community-wide effects are unexplored research topics in this area. This analysis provided the list of top publications, journals, and research hotspots. This study gives a brief overview of the research trends that have been done so far and lay the groundwork for future researchers.

Abbreviations

ICCPI: Impact of climate change on plant-pollinator interactions
IF: Impact factor
JCR: Journal Citation Report

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Authors' contributions

Pooja Singh: Data curation, Formal analysis, Investigation, Methodology, Software, Writing the first draft. Vishal Tripathi: Formal analysis, Validation, Writing - review & editing. V.P. Uniyal: Methodology, Project administration, Supervision, Writing - review & editing. Prabhakar Semwal: Conceptualization, Investigation, Project administration, Supervision, Writing - review & editing.

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Availability of data and materials
All data and materials related to this study have been included in this manuscript and are freely available in the Scopus database.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

References

Aldridge G, Inouye DW, Forrest JRK, Barr WA, Miller-Rushing AJ. Emergence of a mid-season period of low floral resources in a montane meadow ecosystem associated with climate change. J Ecol. 2011;99(4):905-13. https://doi.org/10.1111/j.1365-2745.2011.01826.x.

Alzate-Marin AL, Rivas PMS, Galaschi-Teixeira JS, Bonifácio-Anacleto F, Silva CC, Schuster I, et al. Warming and elevated CO_2 induces changes in the reproductive dynamics of a tropical plant species. Sci Total Environ. 2021;768:144899. https://doi.org/10.1016/j.scitotenv.2020.144899.

Aria M, Cuccurullo C. *bibliometrix*: an R-tool for comprehensive science mapping analysis. J Informet. 2017;11(4):959-75. https://doi.org/10.1016/j.joi.2017.08.007.

Bartomeus I, Ascher JS, Wagner D, Danforth BN, Colla S, Kornbluth S, et al. Climate-associated phenological advances in bee pollinators and bee-pollinated plants. Proc Natl Acad Sci U S A. 2011;108(51):20645-9. https://doi.org/10.1073/pnas.1115559108.

Belter CW. Bibliometric indicators: opportunities and limits. J Med Libr Assoc. 2015;103(4):219-21. https://doi.org/10.3163/1536-5050.103.4.014.

Brunet J, Fragoso FP. What are the main reasons for the worldwide decline in pollinator populations? CABI Reviews. 2024;19:1. https://doi.org/10.1079/cabireviews.2024.0016.

Burkle LA, Alarcón R. The future of plant–pollinator diversity: understanding interaction networks across time, space, and global change. Am J Bot. 2011;98(3):528-38. https://doi.org/10.3732/ajb.1000391.

Burkle LA, Marlin JC, Knight TM. Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function. Science. 2013;339(6127):1611-5. https://doi.org/10.1126/science.1232728.

Buxton MN, Gaskett AC, Lord JM, Pattemore DE. A global review demonstrating the importance of nocturnal pollinators for crop plants. J Appl Ecol. 2022;59(12):2890-901. https://doi.org/10.1111/1365-2664.14284.

Chakraborty A, Chaudhury R, Dutta S, Basak M, Dey S, Schäffner AR, et al. Role of metabolites in flower development and discovery of compounds controlling flowering time. Plant Physiol Biochem. 2022;190:109-18. https://doi.org/10.1016/j.plaphy.2022.09.002.

Cook BI, Wolkovich EM, Parmesan C. Divergent responses to spring and winter warming drive community level flowering trends. Proc Natl Acad Sci U S A. 2012;109(23):9000-5. https://doi.org/10.1073/pnas.1118364109.

da Silva MA, Ferreira NdS, Teixeira-Souza VHdS, Maia-Silva C, de Oliveira FdA, Hrncir M. On the thermal limits for the use of stingless bees as pollinators in commercial greenhouses. J Apic Res. 2017;56(1):81-90. https://doi.org/10.1080/00218839.2016.1260380.

de Sassi C, Tylianakis JM. Climate change disproportionately increases herbivore over plant or parasitoid biomass. PLoS One. 2012;7(7):e40557. https://doi.org/10.1371/journal.pone.0040557.

de Zwaan DR, Scridel D, Altamirano TA, Gokhale P, Kumar RS, Sevillano-Ríos S, et al. GABB: a global dataset of alpine breeding birds and their ecological traits. Sci Data. 2022;9:627. https://doi.org/10.1038/s41597-022-01723-6.

Descamps C, Quinet M, Jacquemart AL. Climate change-induced stress reduce quantity and alter composition of nectar and pollen from a bee-pollinated species (*Borago officinalis*, Boraginaceae). Front Plant Sci. 2021;12:755843. https://doi.org/10.3389/fpls.2021.755843.

Donthu N, Kumar S, Mukherjee D, Pandey N, Lim WM. How to conduct a bibliometric analysis: an overview and guidelines? J Bus Res. 2021;133:285-96. https://doi.org/10.1016/j.jbusres.2021.04.070.

Doré M, Fontaine C, Thébault E. Relative effects of anthropogenic pressures, climate, and sampling design on the structure of pollination networks at the global scale. Glob Chang Biol. 2021;27(6):1266-80. https://doi.org/10.1111/gcb.15474.

Dupont YL, Padrón B, Olesen JM, Petanidou T. Spatio-temporal variation in the structure of pollination networks. Oikos. 2009;118(8):1261-9. https://doi.org/10.1111/j.1600-0706.2009.17594.x.

Elle E, Elwell SL, Gielens GA. The use of pollination networks in conservation. Botany. 2012;90(7):525-34. https://doi.org/10.1139/B11-111.

Ellegaard O, Wallin JA. The bibliometric analysis of scholarly production: how great is the impact? Scientometrics. 2015;105(3):1809-31. https://doi.org/10.1007/s11192-015-1645-z.

Elmqvist T, Folke C, Nyström M, Peterson G, Bengtsson J, Walker B, et al. Response diversity, ecosystem change, and resilience. Front Ecol Environ. 2023;1(9):488-94. https://doi.org/10.1890/1540-9295(2003)001[0488:RDECAR]2.0.CO;2.

Forrest JRK. Plant-pollinator interactions and phenological change: what can we learn about climate impacts from experiments and observations? Oikos. 2015;124(1):4-13. https://doi.org/10.1111/oik.01386.

Forrest JRK, Thomson JD. An examination of synchrony between insect emergence and flowering in Rocky Mountain meadows. Ecol Monogr. 2011;81(3):469-91. https://doi.org/10.1890/10-1885.1.

Gallagher MK, Campbell DR. Shifts in water availability mediate plant-pollinator interactions. New Phytol. 2017;215(2):792-802. https://doi.org/10.1111/nph.14602.

Gambel J, Holway DA. Divergent responses of generalist and specialist pollinators to experimental drought: outcomes for plant reproduction. Ecology. 2023;104(8):e4111. https://doi.org/10.1002/ecy.4111.

Hamann E, Blevins C, Franks SJ, Jameel MI, Anderson JT. Climate change alters plant-herbivore interactions. New Phytol. 2021;229(4):

1894-910. https://doi.org/10.1111/nph.17036.

Handley JC, Tronstad LM. Pollinators limit seed production in an early blooming rare plant: evidence of a mismatch between plant phenology and pollinator emergence. Nord J Bot. 2023;2023(7):e03877. https://doi.org/10.1111/njb.03877.

Harrison T, Winfree R. Urban drivers of plant-pollinator interactions. Funct Ecol. 2015;29(7):879-88. https://doi.org/10.1111/1365-2435.12486.

Hegland SJ, Nielsen A, Lázaro A, Bjerknes AL, Totland Ø. How does climate warming affect plant-pollinator interactions? Ecol Lett. 2009;12(2):184-95. https://doi.org/10.1111/j.1461-0248.2008.01269.x.

Hemberger JA, Rosenberger NM, Williams NM. Experimental heatwaves disrupt bumblebee foraging through direct heat effects and reduced nectar production. Funct Ecol. 2023;37(3):591-601. https://doi.org/10.1111/1365-2435.14241.

Hilário S, Pinto G, Monteiro P, Santos L, Alves A. The impact of two *Diaporthe* species on *Vaccinium corymbosum* physiological performance under different water availability scenarios. Eur J Plant Pathol. 2023;166(2):161-77. https://doi.org/10.1007/s10658-023-02651-w.

Höfer RJ, Lindner T, Ayasse M, Kuppler J. Reduced seed set under water deficit is driven mainly by reduced flower numbers and not by changes in flower visitations and pollination. Funct Ecol. 2023;37(2):461-71. https://doi.org/10.1111/1365-2435.14233.

Kawata S, Takimoto G. Pollinator predation stabilizes plant–pollinator mutualisms through the modification of pollinator behavior. Ecol Res. 2023;38(2):360-6. https://doi.org/10.1111/1440-1703.12376.

Klarin A. How to conduct a bibliometric content analysis: guidelines and contributions of content co-occurrence or co-word literature reviews. Int J Consum Stud. 2024;48(2):e13031. https://doi.org/10.1111/ijcs.13031.

Knop E, Zoller L, Ryser R, Gerpe C, Hörler M, Fontaine C. Artificial light at night as a new threat to pollination. Nature. 2017;548(7666):206-9. https://doi.org/10.1038/nature23288.

Kreyling J. Winter climate change: a critical factor for temperate vegetation performance. Ecology. 2010;91(7):1939-48. https://doi.org/10.1890/09-1160.1.

Kudo G, Ida TY. Early onset of spring increases the phenological mismatch between plants and pollinators. Ecology. 2013;94(10):2311-20. https://doi.org/10.1890/12-2003.1.

Lu X, Siemann E, Shao X, Wei H, Ding J. Climate warming affects biological invasions by shifting interactions of plants and herbivores. Glob Chang Biol. 2013;9(8):2339-47. https://doi.org/10.1111/gcb.12244.

Marshman J, Blay-Palmer A, Landman K. Anthropocene crisis: climate change, pollinators, and food security. Environments. 2019;6(2):22. https://doi.org/10.3390/environments6020022.

Memmott J, Craze PG, Waser NM, Price MV. Global warming and the disruption of plant-pollinator interactions. Ecol Lett. 2007;10(8):710-7. https://doi.org/10.1111/j.1461-0248.2007.01061.x.

Minachilis K, Kantsa A, Devalez J, Trigas P, Tscheulin T, Petanidou T. Bumblebee diversity and pollination networks along the elevation gradient of Mount Olympus, Greece. Diversity Distrib. 2020;26(11):1566-81. https://doi.org/10.1111/ddi.13138.

Mitchell RJ, Irwin RE, Flanagan RJ, Karron JD. Ecology and evolution of plant-pollinator interactions. Ann Bot. 2009;103(9):1355-63. https://doi.org/10.1093/aob/mcp122.

Mohammed M, Li J. Knowledge mapping and visualization of current sarcopenia and cancer research: a bibliometric analysis. Beni-Suef Univ J Basic Appl Sci. 2023;12:51. https://doi.org/10.1186/s43088-023-00386-5.

Møller A, Myles P. What makes a good systematic review and meta-analysis? Br J Anaesth. 2016;117(4):428-30. http://dx.doi.org/10.1093/bja/aew264.

Munguía-Rosas MA, Ollerton J, Parra-Tabla V, De-Nova JA. Meta-analysis of phenotypic selection on flowering phenology suggests that early flowering plants are favoured. Ecol Lett. 2011;14(5):511-21. https://doi.org/10.1111/j.1461-0248.2011.01601.x.

Nath R, Singh H, Mukherjee S. Insect pollinators decline: an emerging concern of Anthropocene epoch. J Apic Res. 2023;62(1):23-38. https://doi.org/10.1080/00218839.2022.2088931.

Olsen SL, Evju M, Åström J, Løkken JO, Dahle S, Andresen JL, et al. Climate influence on plant–pollinator interactions in the keystone species *Vaccinium myrtillus*. Ecol Evol. 2022;12(5):e8910. https://doi.org/10.1002/ece3.8910.

Ostap-Chec M, Kierat J, Kuszewska K, Woyciechowski M. Red mason bee (*Osmia bicornis*) thermal preferences for nest sites and their effects on offspring survival. Apidologie. 2012;52:707-19. https://doi.org/10.1007/s13592-021-00858-6.

Ovaskainen O, Skorokhodova S, Yakovleva M, Sukhov A, Kutenkov A, Kutenkova N, et al. Community-level phenological response to climate change. Proc Natl Acad Sci U S A. 2013;110(33):13434-9. https://doi.org/10.1073/pnas.1305533110.

Pelayo RC, Llambí LD, Gámez LE, Barrios YC, Ramirez LA, Torres JE, et al. Plant phenology dynamics and pollination networks in summits of the high tropical andes: a baseline for monitoring climate change impacts. Front Ecol Evol. 2021;9:679045. https://doi.org/10.3389/fevo.2021.679045.

Peng C, He M, Cutrona SL, Kiefe CI, Liu F, Wang Z. Theme trends and knowledge structure on mobile health apps: bibliometric analysis. JMIR Mhealth Uhealth. 2020;8(7):e18212. https://doi.org/10.2196/18212.

Plos C, Stelbrink N, Römermann C, Knight TM, Hensen I. Abiotic conditions affect nectar properties and flower visitation in four herbaceous plant species. Flora: Morphol Distrib Funct Ecol Plants. 2023;303:152279. https://doi.org/10.1016/j.flora.2023.152279.

Post E, Forchhammer MC. Climate change reduces reproductive success of an Arctic herbivore through trophic mismatch. Philos Trans R Soc Lond B Biol Sci. 2008;363(1501):2369-75. https://doi.org/10.1098/rstb.2007.2207.

Potts SG, Ngo HT, Biesmeijer JC, Breeze TD, Dicks TD, Garibaldi LA, et al. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. Bonn, Germany: Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; 2016.

Primack RB, Ibáñez I, Higuchi H, Lee SD, Miller-Rushing AJ, Wilson AM, et al. Spatial and interspecific variability in phenological responses to warming temperatures. Biol Conserv. 2009;142(11):2569-77. https://doi.org/10.1016/j.biocon.2009.06.003.

Rafferty NE, Diez JM, Bertelsen CD. Changing climate drives divergent and nonlinear shifts in flowering phenology across elevations. Curr Biol. 2020;30(3):432-41.e3. https://doi.org/10.1016/j.cub.2019.11.071.

Rafferty NE, Ives AR. Effects of experimental shifts in flowering phenology on plant-pollinator interactions. Ecol Lett. 2011;14(1):69-74. https://doi.org/10.1111/j.1461-0248.2010.01557.x.

Ren P, Néron V, Rossi S, Liang E, Bouchard M, Deslauriers A. Warming counteracts defoliation-induced mismatch by increasing herbivore-plant phenological synchrony. Glob Chang Biol. 2020;26(4): 2072-80. https://doi.org/10.1111/gcb.14991.

Santamaría S, Sánchez AM, López-Angulo J, Ornosa C, Mola I, Escudero A. Landscape effects on pollination networks in Mediterranean gypsum islands. Plant Biol. 2018;20:184-94. https://doi.org/10.1111/plb.12602.

Schweiger O, Biesmeijer JC, Bommarco R, Hickler T, Hulme PE, Klotz S, et al. Multiple stressors on biotic interactions: how climate change and alien species interact to affect pollination. Biol Rev. 2010;85(4): 777-95. https://doi.org/10.1111/j.1469-185X.2010.00125.x.

Singh AP, De K, Uniyal VP, Sathyakumar S. Unveiling of climate change-driven decline of suitable habitat for Himalayan bumblebees. Sci Rep. 2024a;14(1):4983. https://doi.org/10.1038/s41598-024-52340-9.

Singh P, Gargi B, Semwal P, Verma S. Global research and research progress on climate change and their impact on plant phenology: 30 years of investigations through bibliometric analysis. Theor Appl Climatol 2024b;155:4909-23. https://doi.org/10.1007/s00704-024-04919-5.

Singh P, Gargi B, Trivedi V, Thapliyal A, Semwal P. Global research progress on reproductive behavior and ethnobotany of the Saussurea genus: literature review-based-bibliometric analysis. Ethnobot Res Appl. 2023;26:1-15.

St-Onge J, Renaud-Desjardins L, Mongeau P, Saint-Charles J. Socio-semantic networks as mutualistic networks. Sci Rep. 2022;12:1889. https://doi.org/10.1038/s41598-022-05743-5.

Sutton TL, DeGabriel JL, Riegler M, Cook JM. A temperate pollinator with high thermal tolerance is still susceptible to heat events predicted under future climate change. Ecol Entomol. 2018;43(4):506-12. https://doi.org/10.1111/een.12528.

Thuma JA, Duff C, Pitera M, Januario N, Orians CM, Starks PT. Nutrient enrichment and rainfall affect plant phenology and floral resource availability for pollinators. Front Ecol Evol. 2023;11:1150736. https://doi.org/10.3389/fevo.2023.1150736.

van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2010;84:523-38. https://doi.org/10.1007/s11192-009-0146-3.

van Raan AFJ. Advances in bibliometric analysis: research performance assessment and science mapping. In: Blockmans W, Engwall L, Weaire D, editors. Bibliometrics use and abuse in the review of research performance. London: Portland Press; 2014. p. 17-28.

Villagomez GN, Nürnberger F, Requier F, Schiele S, Steffan-Dewenter I. Effects of temperature and photoperiod on the seasonal timing of Western honey bee colonies and an early spring flowering plant. Ecol Evol. 2021;11(12):7834-49. https://doi.org/10.1002/ece3.7616.

Waser NM, Price MV. Drought, pollen and nectar availability, and pollination success. Ecology. 2016;97(6):1400-9. https://doi.org/10.1890/15-1423.1.

Xiao Y, Li X, Cao Y, Hu W. A global change of specialization and generalization in pollination networks from the plant perspective. Russ J Ecol. 2017;48(2):143-51. https://doi.org/10.1134/S1067413617220027.

Yin R, Qin W, Wang X, Xie D, Wang H, Zhao H, et al. Experimental warming causes mismatches in alpine plant-microbe-fauna phenology. Nat Commun. 2023;14(1):2159. https://doi.org/10.1038/s41467-023-37938-3.

Zamora-Gutierrez V, Rivera-Villanueva AN, Martínez Balvanera S, Castro-Castro A, Aguirre-Gutiérrez J. Vulnerability of bat–plant pollination interactions due to environmental change. Glob Chang Biol. 2021;27(14):3367-82. https://doi.org/10.1111/gcb.15611.

Zoller L, Bennett J, Knight TM. Plant–pollinator network change across a century in the subarctic. Nat Ecol Evol. 2023;7(1):102-12. https://doi.org/10.1038/s41559-022-01928-3.