GMR
The Original

CLIMATE CHANGE AND MULTI-STRESSOR IMPACTS ON SOLITARY BEES IN AGROECOSYSTEMS: ECOLOGY, EMERGING TECHNOLOGIES AND CLIMATE-RESILIENT CONSERVATION STRATEGIES

Megavathi Thirunavukkarasu[1], Suresh Krishnasamy[1*], Usharani Balakrishnan[2], Rajamanickam Chinnapalani[2], Manonmani Karunakaran[2], Saai Vignesh Balakrishnan[2], Udhayanandhini Alagarraj[2] and Ramasamy Kanagaraj Murali-Baskaran[3]

[1]ICAR-Krishi Vigyan Kendra, Agricultural College and Research Institute, Madurai 625 104, Tami Nadu, India.
[2]Department of Agricultural Entomology, Agricultural College and Research Institute, Madurai, 625 104, Tamil Nadu, India.
[3]ICAR-National Institute of Biotic Stress Management, Raipur 493 225, Chhattisgarh, India.
*Correspondence: Suresh Krishnasamy (suresh.k@tnau.ac.in)

ABSTRACT

Solitary bees are one of the most biodiverse and efficient pollinators in nature and they play a vital role in biodiversity, ecological processes, and also agriculture. But now their population is threatened by climate change. This review will analyze scientific literatures about the effects of climate change on the ecology and conservation of solitary bees. Phenology, physiology, reproductive ecology, species distribution, pollination services, conservation of climate change will also be analyzed. Information about interaction of climate change with habitat fragmentation, pesticides, nutritional stress and microbiome was critically reviewed. climate change greatly affects the phenology, distribution, reproductive efficiency, and pollination services of solitary bees. Species specific traits like thermal tolerance, nesting strategy, dispersal ability, and dietary specialization, largely determines the vulnerability and resilience to climate change. Multiple stressors act synergistically in order to reduce bee fitness and population stability. Emerging technologies like environmental DNA, remote sensing, artificial intelligence, and ecological forecasting offer new opportunities for pollinators monitoring and adaptive management strategies. Climate change poses a major threat to solitary bee diversity and also to the ecosystem services that are provided by them. Integrated conservation strategies that restore habitats, enhance floral and nesting resources, and by diversifying landscapes, and mitigating pesticide risk would be some supporting factors. A climate resilient solitary bee conservation framework is proposed to support evidence-based conservation and sustainable pollination services under future environmental change.

KEYWORDS: Solitary bees; Climate change; Multi-stressor interactions; Pollinator conservation; Emerging technologies; Agroecosystems

INTRODUCTION

Pollination is a crucial ecological process that supports the maintenance of biological diversity and global food production, with the wild pollinators playing a significant role in enhancing crop yield, quality, and stability in the ecosystem (Dainese et al., 2019). The economic impact of animal mediated pollination is estimated to be several billions of USD each year underscoring its essential contribution to agricultural productivity and food security. While managed pollinators like *Apis mellifera* are important for crop production, growing evidence suggest that wild pollinators, especially solitary bees, often demonstrate higher pollination efficiency per visit and have a disproportionately positive impact on crop yield, fruit and yield stability (Garibaldi et al., 2021). Moreover, diverse wild bee population enhances the stability of pollination services in the dace of environmental changes trough functional complementarity and redundancy (Dainese et al., 2019; Wood et al., 2015). As result the conservation of solitary bee diversity is not only an ecological imperative but also an economic necessity for the sustainability of climate resilient agroecosystem. Among the wild pollinators, solitary bees constitute highly diverse and functionally significant group, which are distinguished by their independent nesting behaviour, morphological traits and specialized actions that often leads to greater pollination efficiency compared to managed species (Garibaldi et al., 2021; Garratt et al., 2023). Their population and effectiveness are heavily influenced by habitat structure, landscape composition, and also the availability of varied floral and nesting resources (Dainese et al., 2019). Semi-natural environments such as field margin, hedgerows and grasslands offer important resources which aids in population sustainability and ecosystem functionality (Wood et al.,2015). However the increasing anthropogenic pressures, like intensified agriculture, pesticide exposure, and climate change are progressively disrupting these systems, which results in decline in pollinator diversity and the services provided by them (Wagner,2020; Van der sluijs et al., 2023; dicks et al., 2021). Phenological changes like earlier emergence and altered flowering periods, often creates mismatches between bees and their floral resources, leading to decreased foraging efficiency and reproductive success (Kudo and Cooper 2019; CaraDonna et al.,2021). Thermal stress and nutritional deficiencies further hinder the survival, fecundity, and the development if offsprings (Hoover et al., 2024; Descamps et al., 2021). On a larger spatial scale, climate-induced changes are shifts in habitats and species ranges that are driven by climate impact specialist species and tropical pollinator communities more severely, intensifying the biodiversity loss and collapsing the ecosystem resilience (Herrera, 2023). Importantly, solitary bees are affected by climate change alongside various interacting stressor. The warming climate interacts with habitat loss, pesticide exposure, nutritional stress, and biological invasions, resulting in non-linear and often worsens the effects on bee population (Goulson et al., 2015; Harrison et al., 2026). These interactions limit the energy allocation, disrupts microbiome-mediated functions, and diminish adaptive capacity, thereby accelerating population declines (Hammer et al., 2021; Filipiak, 2024). Nonetheless, the majority of research has concerntrated on individual or dual stressors, which restricts our capacity to forecast ecological responses and formulate adaptive conservation strategies in context of global change scenarios (Alves-dos-Santos, 2025). Recent investigations further reveal that species responses to climate change are significantly influenced by thermal physiology, diapause regulation, reproductive ecology, nesting biology and functional traits such as body size, phenology, dispersal ability, and dietary specialization. As result the conservation strategies for solitary bees have evolved from localized to integrated, and climate resilient approches. Initiatives such as habitat restoration, enhancement of floral and nesting resource, diversification of agroecosystem, and mitigation of pesticide risks can significantly bloster the pollination populations and the delivery of ecosystem services (Haaland et al., 2011; Fortel et al., 2021; Fahrig et al., 2015; Kremen et al., 2021). However, the effectiveness of the strategies under rapidly changing climatic conditions remain uncertain, especially in tropical regions that host remarkable pollinator diversity yet are underrepresented in climate change research (Kennedy et al., 2019; Leong et al., 2025). Recent developments in emerging technologies, such as environmental DNA (eDNA), remote sensing, artificial intelligence, automates monitoring systems, and ecological forecasting, presents unparalled opportunities to enhance the monitoring of pollinators, assess their vulnerabilities and plan for the conservation strategies (Høye et al., 2025; Hartig et al., 2024). However, significant gaps persist in the integration of climate change, multi stressor interaction, physiological mechanisms, species-specific responses, and conservation strategies within a cohesive conceptual framework. And there are notable geographical biases, particularly the insufficient representation of tropical agroecosystems and the lack of long-term studies focused on solitary bee ecology (Haddaway et al., 2015).

SYSTEMATIC REVIEW METHODOLOGY

Literature Search Strategy

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines in order to ensure transparency, reproducibility, and comprehensive synthesis of the available literature. A systematic search was conducted using four major scientific databases: Web of Science Core Collection, Scopus, PubMed, and Google Scholar. Literature published between January 2000 and March 2026 was considered to capture recent advances in climate change biology, pollinator ecology, and conservation science. The following search string was employed: ("solitary bee*" OR "wild bee*" OR "non-Apis bee*") AND ("climate change" OR warming OR "global change" OR temperature OR drought OR precipitation) AND (pollination OR conservation OR agroecosystem* OR biodiversity).

Additional searches were performed using combinations of the following terms:

- solitary bees AND phenology;
- solitary bees AND thermal tolerance;
- solitary bees AND diapause;
- solitary bees AND pesticide exposure;
- solitary bees AND trait-based ecology;
- solitary bees AND conservation;
- solitary bees AND emerging technologies;
- pollinator climate resilience;
- tropical pollinators AND climate change.

Reference lists of selected articles and recent review papers were further screened to identify additional relevant publications.

Inclusion and Exclusion Criteria

Studies were included if they: (i) investigated the effects of climate change or climate-associated stressors on solitary bees; (ii) examined pollination services, physiological responses, reproductive ecology, species distributions, trait-mediated adaptation, conservation strategies, or emerging technologies; (iii) included empirical, experimental, modelling, bibliometric, or review-based evidence relevant to agroecosystems and natural ecosystems; and (iv) were published in peer-reviewed journals in English. Studies were excluded if they: (i) focused exclusively on managed honey bees (*Apis mellifera*) without considering solitary bees; (ii) lacked sufficient methodological information; (iii) were conference abstracts, editorials, theses, duplicate publications, or non-peer-reviewed reports; or (iv) were unrelated to climate change, pollinator ecology, or solitary bee conservation.

Study Selection Process

All retrieved records were exported to Mendeley Reference Manager, and duplicate entries were removed. Titles and abstracts were independently screened for relevance, followed by full-text assessment according to the inclusion and exclusion criteria. The study selection process followed the PRISMA 2020 workflow comprising identification, screening, eligibility assessment, and final inclusion. A total of 1,247 records were initially identified from the databases. After removing duplicates (n = 278), 969 articles remained for title and abstract screening. Subsequently, 624 articles were excluded because they did not address solitary bees or climate-related factors. The full texts of 345 articles were evaluated for eligibility, of which 184 articles were excluded for failing to satisfy the inclusion criteria. Finally, 161 publications were included in this review and formed the basis for qualitative synthesis and bibliometric assessment (Table 1; Fig. 5).

Table 1. Ecosystem-service assessment frameworks and decision-support tools for evaluating pollination services under climate change

Tool	Main application	Major output	Key advantage	Main limitation
InVEST	Conservation planning	Pollination maps	Spatially explicit	Data intensive
ARIES	Service-flow assessment	Scenario analysis	Flexible and integrative	Complex implementation
TESSA	Site-level assessment	Ecosystem indicators	User-friendly	Limited scalability
Natural Capital Project	Policy and valuation	Natural-capital accounts	Strong policy relevance	Requires interdisciplinary datasets
SDMs	Climate adaptation	Vulnerability maps	Long-term forecasting	Projection uncertainty
Economic valuation	Cost-benefit analysis	Monetary estimates	Policy communication	Undervalues non-market benefits

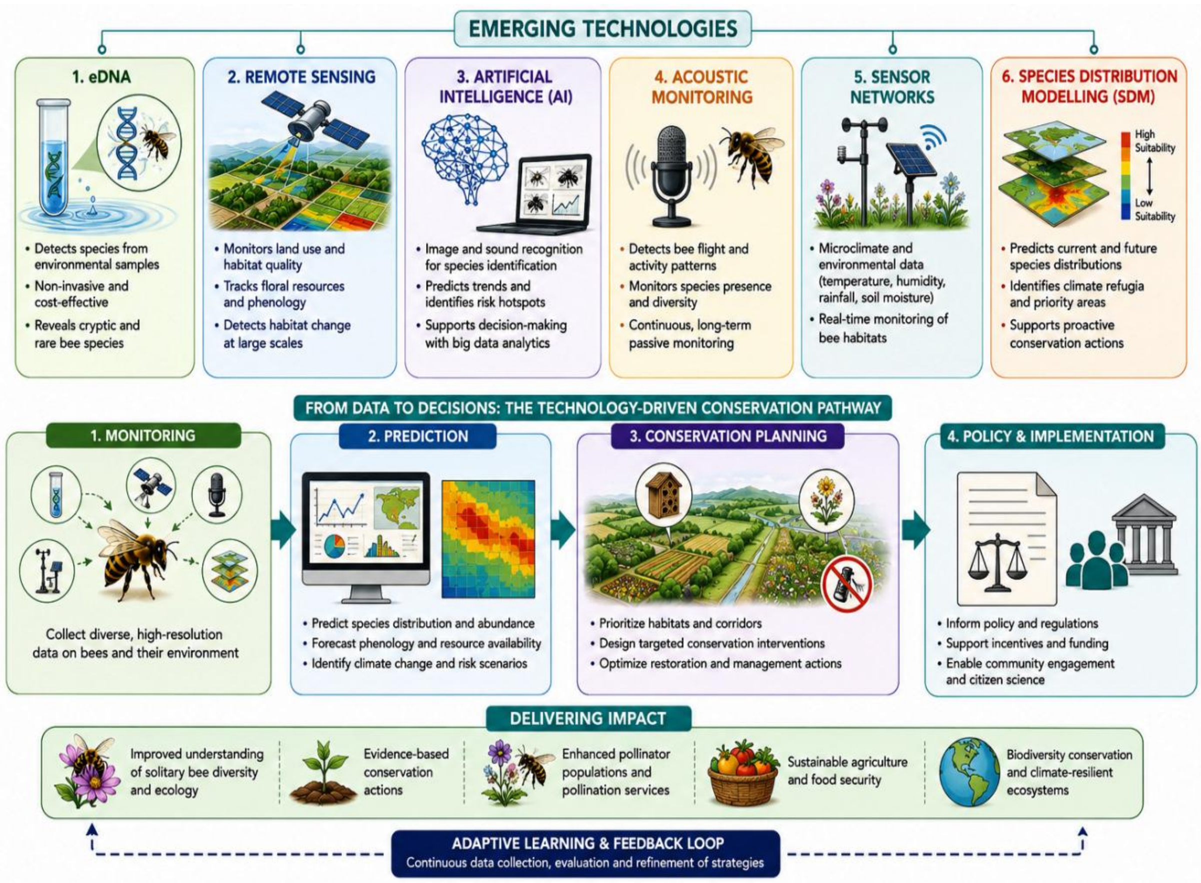


Figure S5. Emerging technologies for monitoring and conserving solitary bees under climate change. Technological approaches including environmental DNA (eDNA), remote sensing, artificial intelligence, acoustic monitoring, sensor networks, and species distribution modelling facilitate monitoring, prediction, conservation planning, and policy implementation, ultimately supporting biodiversity conservation and climate-resilient agricultural systems.

Data Extraction and Synthesis

Information extracted from each study included:

- geographical location and ecosystem type;
- solitary bee taxa investigated;
- climate drivers and environmental stressors examined;
- physiological, behavioural, and ecological response variables;
- pollination services and ecosystem functions;
- conservation interventions and management strategies;
- emerging technologies and modelling approaches;
- principal findings, research gaps, and future priorities.

The selected literature was synthesized qualitatively and organized into the following thematic categories:

1. pollination by solitary bees;
2. climate-change impacts on solitary bees;
3. thermal physiology, diapause, and trait-mediated adaptation;
4. species-specific responses of major taxa;
5. multi-stressor interactions;
6. climate-resilient conservation strategies;
7. tropical agroecosystems;
8. pesticide-risk mitigation;
9. emerging technologies and predictive monitoring; and
10. research gaps and future directions.

Limitations

Several limitations must be acknowledged despite a thorough search of the literature. In addition, geographical biases are still strong, with most of these studies coming from Europe and north America, while tropical areas and developing region remains unexplored. This imbalance might restrict the extrapolation of results to very diverse tropical agroecosystems. And also, there are lots of variation in methods used at spatial scales and response variables among studies making direct comparisons and quantitative meta-analysis. The availability of long-term dataset is very much limited and vast majority only examines the effects of single or pairwise stressors, however the systematic evidence synthesis is a large-scale method of tracking research trends, knowledge gaps and future priorities

Rationale for Bibliometric Analysis

Considering that the scientific literature on climate change and pollinator ecology has expanded rapidly during the past two decades, qualitative synthesis alone may not adequately reveal the emerging research themes, collaboration networks, and geographical biases. Therefore, a bibliometric analysis was conducted to complement the systematic review and provide a quantitative overview of global research trends, thematic evolution, and future priorities in climate change and solitary bee research.

Bibliometric Analysis of Research Trends on Climate Change and Solitary Bees

Data Collection and Bibliographic Database

To identify global research trends, emerging themes, and knowledge gaps in climate change and solitary bee research, a bibliometric analysis was conducted following established approaches for science mapping and quantitative literature synthesis (Donthu et al., 2021). Bibliographic records were retrieved from the Web of Science Core Collection and Scopus databases because of their extensive coverage of peer-reviewed scientific literature and their widespread use in bibliometric investigations. The following search query was employed: ("solitary bee*" OR "wild bee*" OR "non-Apis bee*") AND ("climate change" OR warming OR "global change" OR temperature OR drought OR precipitation). The search was restricted to articles and review papers published between January 2000 and March 2026.

The bibliographic information extracted included:

- authors;
- publication year;
- article title;
- keywords;
- abstracts;
- affiliations;
- journal source;
- citation data; and
- country of origin.

Bibliometric Analysis Procedures
Bibliometric analyses were conducted using the Bibliometrix package in R, whereas network visualization and clustering analyses were performed using VOSviewer.
The following indicators were evaluated:

1. Annual scientific production;
2. Most productive countries and institutions;
3. Leading journals and authors;
4. Citation structure and influential publications;
5. Co-authorship and collaboration networks;
6. Keyword co-occurrence patterns; and
7. Thematic evolution and research hotspots.

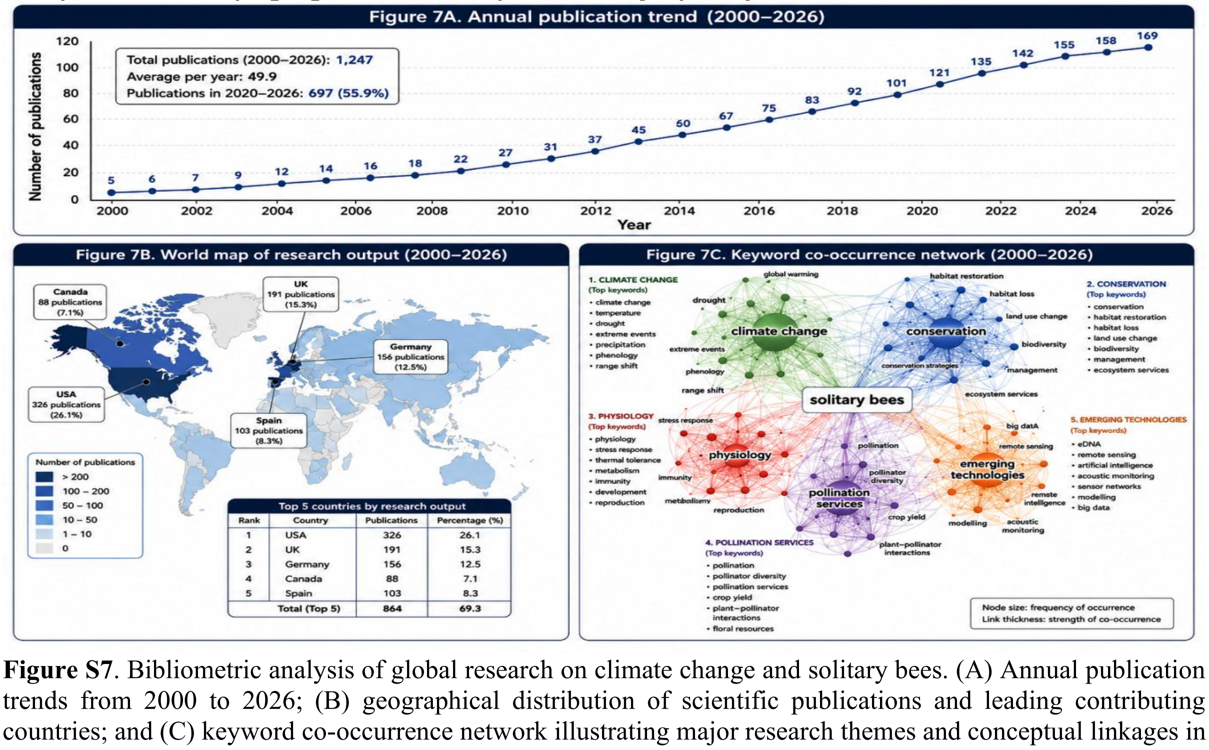
To improve consistency, keyword standardization was performed by merging synonymous terms, including:

- climate change and global warming;
- solitary bee and wild bee;
- pollinator decline and pollinator conservation.

The bibliometric analysis was used to complement the systematic review by identifying research trajectories, geographical biases, and emerging areas of investigation that are not readily apparent through narrative synthesis alone.

Publication Trends and Scientific Production
The number of publications addressing climate change and solitary bees has increased markedly during the past decade, reflecting growing concern regarding pollinator declines, ecosystem resilience, and food security. Publication output accelerated substantially after 2015, coinciding with increased recognition of the ecological and economic importance of wild pollinators and greater research attention toward biodiversity conservation and climate adaptation. The increasing rate of scientific production also reflects a transition from descriptive studies of pollinator ecology toward mechanistic and predictive investigations addressing physiological responses, ecosystem services, and climate-resilient management strategies.

Geographical Distribution and Research Biases
Research activity is strongly concentrated in Europe and North America, with the United States, the United Kingdom, Germany, Canada, and Spain accounting for the majority of publications. In contrast, tropical regions, including South Asia, Africa, and South America, remain substantially underrepresented despite harbouring exceptionally high solitary bee diversity and numerous pollinator-dependent cropping systems. This geographical imbalance limits our understanding of pollinator responses in regions expected to experience severe climate impacts and constrains the development of globally applicable conservation strategies. Expanding research efforts in tropical and developing regions therefore represents a major priority for future studies.



Top 5 countries by research output

Rank	Country	Publications	Percentage (%)
1	USA	326	26.1
2	UK	191	15.3
3	Germany	156	12.5
4	Canada	88	7.1
5	Spain	103	8.3
	Total (Top 5)	864	69.3

Figure S7. Bibliometric analysis of global research on climate change and solitary bees. (A) Annual publication trends from 2000 to 2026; (B) geographical distribution of scientific publications and leading contributing countries; and (C) keyword co-occurrence network illustrating major research themes and conceptual linkages in solitary bee research.

Keyword Co-occurrence, Research Hotspots, and Thematic Evolution

Keyword network analysis identified five major research clusters:

Cluster 1: Climate change, phenology, range shifts, and temperature.

Cluster 2: Pollination services, agriculture, and ecosystem services.

Cluster 3: Conservation, habitat restoration, and landscape management.

Cluster 4: Thermal tolerance, physiology, diapause, and stress responses.

Cluster 5: Emerging technologies, environmental DNA, remote sensing, artificial intelligence, and machine learning.

The thematic evolution analysis indicates a recent transition from descriptive pollinator ecology toward predictive modelling, trait-based ecology, climate resilience, and technology-assisted conservation (Fig. 6). Major decision-support tools and ecosystem-service assessment frameworks applicable to pollination research and conservation planning are summarized in Table 2.

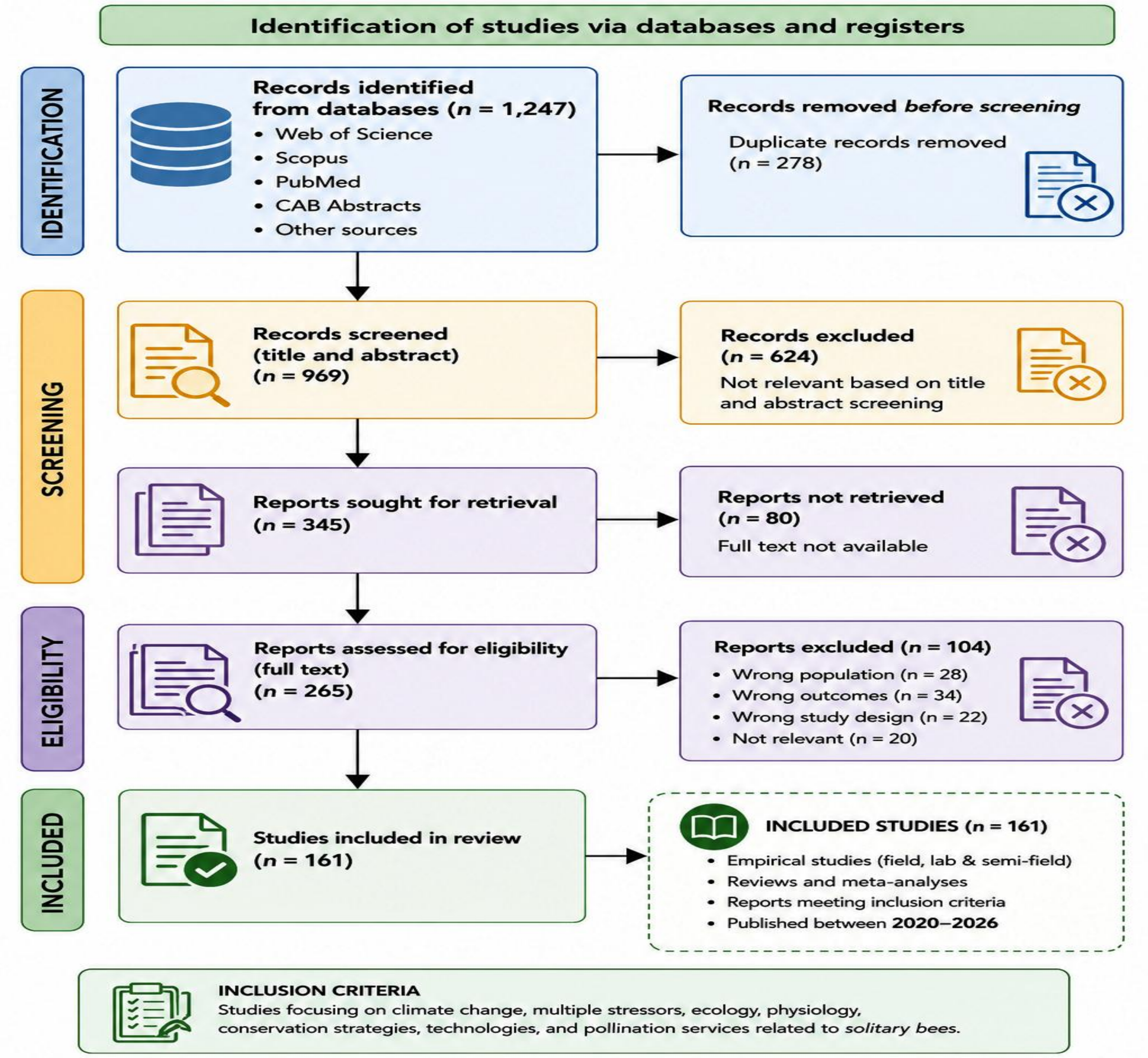


Figure S6. PRISMA flow diagram showing the literature selection process used in this review. The diagram summarizes the identification, screening, eligibility assessment, and inclusion of studies related to climate change, multiple stressors, conservation strategies, technological advances, and pollination services associated with solitary bees.

Table 2. Climate-change impacts on solitary bee biology

Climate driver	Biological response	Ecological consequence	Key references
Rising temperature	Earlier emergence	Phenological mismatch	Forrest (2021)
Drought	Reduced floral resources	Lower reproduction	Hoover et al. (2024)
Heat waves	Reduced longevity	Population decline	Martinet et al. (2024)
Heavy rainfall	Nest destruction	Reduced brood survival	Harrison et al. (2022)

Emerging Research Priorities and Knowledge Gaps

Bibliometric findings demonstrate that research on solitary bees remains geographically biased and taxonomically concentrated on a limited number of model genera, particularly Osmia and Megachile. Studies integrating climate change, physiological mechanisms, trait-mediated responses, and conservation interventions remain comparatively scarce, especially in tropical agroecosystems.

Future research should therefore prioritize:

(i) establishment of long-term monitoring networks;

(ii) expansion of research in tropical and underrepresented pollinator systems;

(iii) multi-factorial experiments incorporating interacting environmental stressors;

(iv) trait-based ecological modelling and vulnerability assessments;

(v) integration of environmental DNA, artificial intelligence, remote sensing, and ecological forecasting into conservation planning; and

(vi) development of predictive and adaptive frameworks linking climate drivers, biological responses, and ecosystem services.

Overall, the bibliometric analysis highlights the rapid growth and diversification of research on climate change and solitary bees while emphasizing persistent knowledge gaps that must be addressed to develop effective, climate-resilient conservation strategies and sustain pollination services in agroecosystems.

Pollination by Solitary Bees

Solitary bees represent one of the most diverse and ecologically significant groups of wild pollinators, playing a crucial role in maintaining biodiversity, supporting ecosystem functions and also enhancing agricultural output. In contrast to eusocial species, solitary bees engage in independent nesting and foraging behaviours which often lead to increased pollination efficiency per visit due to their higher floral constancy, effective pollen transfer, and also minimized interspecific competition (Garibaldi et al., 2021; Garratt et al., 2023). Prominent genera such as Megachile, Osmia, and Andrena promote effective pollination through their specialized behaviours and morphological traits, hence improving fruit set, seed yield and crop quality across varieties of plant species (Wood et al., 2015; Bartomeus et al., 2021). Additionally, characteristics like body size, nesting behaviour, scopal morphology, and foraging range palys an significant role in facilitating efficient pollen deposition and resource partitioning among co-existing species (Drossart et al., 2024; Wood et al., 2015).

Within agroecosystems, solitary bees substantially enhances the stability and efficiency of pollination services, particularly where managed pollinators are limited or unreliable (Garibaldi et al., 2021; Dainese et al., 2019; Sutter et al., 2024). Empirical studies have demonstrated that wild solitary bees improve crop yield and fruit quality in fruits, vegetables, and oilseed crops and frequently exceed the per-visit effectiveness of *Apis mellifera* under field conditions (Garratt et al., 2023). Species-rich pollinator assemblages further enhance pollination reliability through functional complementarity and redundancy, thereby stabilizing ecosystem service delivery under environmental variability (Dainese et al., 2019; Wood et al., 2015; Albrecht et al., 2023).

Recent advances have highlighted the importance of functional trait and network approaches in understanding pollination dynamics and ecosystem resilience. Functional diversity among solitary bees strengthens plant–pollinator network stability, enhances ecosystem multifunctionality, and also buffers pollination services against environmental disturbances (Bartomeus et al., 2021). This stabilizing role is particularly important under global change, where habitat fragmentation, climate variability, and anthropogenic pressures increasingly disrupt pollinator communities and ecosystem functioning (Wagner, 2020; Harrison et al., 2026). Collectively these findings demonstrated that the conserving diverse solitary bee communities are essential for maintaining pollination services and enhancing the resilience of agroecosystems under changing environmental conditions.

Climate Change Impacts on Solitary Bees

Climate change is profoundly affecting the ecology and the life-history dynamics of solitary bees as a result of increasing temperatures, alterations in precipitation patterns and rise in the occurance of extreme weather events (Forrest, 2021). A notable response to those alteration is the change in phenology, where earlier warming in spring results in advanced emergence timings across various taxa, including Osmia and Megachile, this frequently leads to a temporal mismatch with peak availability of floral resources (Kudo and Cooper, 2019; Bartomeus et al., 2021). Such phenological mismatches reduce foraging efficiency and pollen collection, ultimately leading to diminished reproductive success and lower offspring survival rates (CaraDonna et al., 2021). On top of that, climate driven variations in temperature and precipitation disrupt diapause regulation and developmental synchrony, which increases mortality rates during overwintering and the early life stages (Forrest, 2021; Radzevičiūtė et al., 2021). These effects are particularly pronounced in species that possess narrow phenological windows and specific plant associations.

In addition to phenological shifts, increased temperature and extreme weather events place significant physiological limitations on solitary bees, impacting their survival, fitness and reproductive success (Hamblin et al., 2023). Further, climate change has indirect effects mediated by plants, as it alters the availability of nectar and nutritional quality of pollen (Hoover et al., 2024; Descamps et al., 2021; Filipiak, 2024). These nutritional alterations hinder larval development, compromise immune responses and diminish adult performance, highlighting the strong connection between the strong connection between plant physiology and the health of pollinators. At broader spatial scales, climate change drives shift in species distribution, habitat reorganization, and population declines, particularly among specialist and range restricted taxa. Species distribution models predict poleward and elevational shifts, along with and semi- arid ecosystem (Herrera, 2023). Recent findings imply that the variation in thermal tolerance among species, along with metabolic trade-offs, phenological adaptability, and resource specialization, significantly affect how different organisms respond to climate change (Martins et al., 2024). As a result, the effects of climate change are not consistent across different taxa rather they are influenced by functional traits that dictate the levels of vulnerability and resilience in shifting environmental conditions. The principal climate drivers, associated biological responses, and ecological consequences for solitary bees are summarized in Table 2**.**

Thermal tolerance and physiological adaptation

Thermal tolerance varies considerably among solitary bee species and are closely associated with body size, nesting behaviour, activity period, and geographic distribution (Martins et al., 2024). Elevated temperatures increase metabolic demands, disrupt physiological homeostasis, and induce oxidative stress, thereby reducing longevity, impairing flight performance, and lowering reproductive output (Hamblin et al., 2023; Hayes and López-Martínez, 2021). Species that have wider thermal niches and enhanced physiological plasticity typically demonstrate increased resilience to climate fluctuation compared to thermal specialist (Martins et al., 2024). Moreover, prolonged exposure to heatwaves can alter energy allocation and reduce body condition, with potential consequences for foraging efficiency and pollination services (Melone et al., 2024; Herrera et al., 2024).

Diapause physiology and climate sensitivity

Diapause is a critical life-history stage that synchronizes solitary bee development with seasonal resource availability. Temperature-mediated changes in diapause initiation, maintenance, and termination can disrupt developmental timing and emergence synchrony (Forrest, 2021; Radzevičiūtė et al., 2021). Warmer winters frequently increase metabolic expenditure during overwintering, reducing energy reserves required for post-emergence survival and reproduction (Bosch et al., 2010; Sgolastra et al., 2016). Experimental studies on *Osmia* species further demonstrate that altered overwintering conditions influence emergence timing, longevity, and reproductive success (Bosch and Kemp, 2002; Bosch and Kemp, 2004). climate-induced disruption of diapause physiology may have profound implications for population dynamics and plant–pollinator synchrony.

Reproductive ecology under environmental stress

Reproductive success is highly sensitive to environmental conditions since temperature and resource availability directly influences the mating behaviour, fecundity, offspring development, and sex allocation (Bosch and Vicens, 2006). Heat stress has been associated with reduced sperm viability, lowered egg production, and decreased offspring survival, particularly when combined with nutritional limitation (Filipiak, 2024). In addition, climate-induced reductions in pollen quality and availability of floral resources can constrain brood production and larval development (Vaudo et al., 2015; Hoover et al., 2024; Descamps et al., 2021). These reproductive constraints may reduce population growth and increase extinction risk, particularly among specialist species with narrow ecological requirements.

Trait-mediated responses and adaptive capacity

Trait-based approaches are mechanistic explanations for interspecific variation in response to climate change. They are sensitive to environmental stress and their contributions to pollination services that depend on functional traits, including body size, phenology nesting strategy, dispersal ability range and food-item specialization (Bartomeus et al. 2023; Drossart et al., 2024). Species with higher levels of phenotypic plasticity, generalised resource use and flexible nesting are typically more adaptable to changing environments. Integrating trait-based ecology with physiological, demographic, and distributional studies will improve predictions of pollinator resilience, facilitate vulnerability assessments, and guide climate-resilient conservation strategies under future environmental scenarios

Multi-Stressor Interactions Under Climate Change

Climate change affects solitary bees through complex interactions with multiple environmental stressors operating across physiological, ecological, and landscape scales (Goulson et al., 2015). Rising temperatures, altered precipitation regimes, habitat loss, pesticide exposure, nutritional stress, and biological invasions frequently act synergistically, amplifying impacts on bee fitness and population dynamics. Such interactions limit the predictive power of single-factor approaches and underscore the need for integrative frameworks to understand pollinator responses under global change. Solitary bees are particularly vulnerable because many species exhibit limited dispersal capacity, specialized nesting requirements, and dependence on spatially and temporally constrained floral resources (Harrison et al., 2026).

Interacting Thermal and Physiological Stressors

Physiological responses to climate change are further shaped by interactions among thermal, hydric, and developmental stressors. Elevated temperatures impair enzyme function, increase oxidative stress, and reduce survival, particularly during extreme heat events (Martins et al., 2024; Bishop et al., 2023). When combined with low humidity, these conditions intensify desiccation stress, disrupt water balance, and constrain foraging activity. Seasonal warming may also disrupt diapause regulation, by increasing metabolic expenditure and reducing post-emergence fitness, particularly in species such as *Osmia bicornis* (Radzevičiūtė et al., 2021).

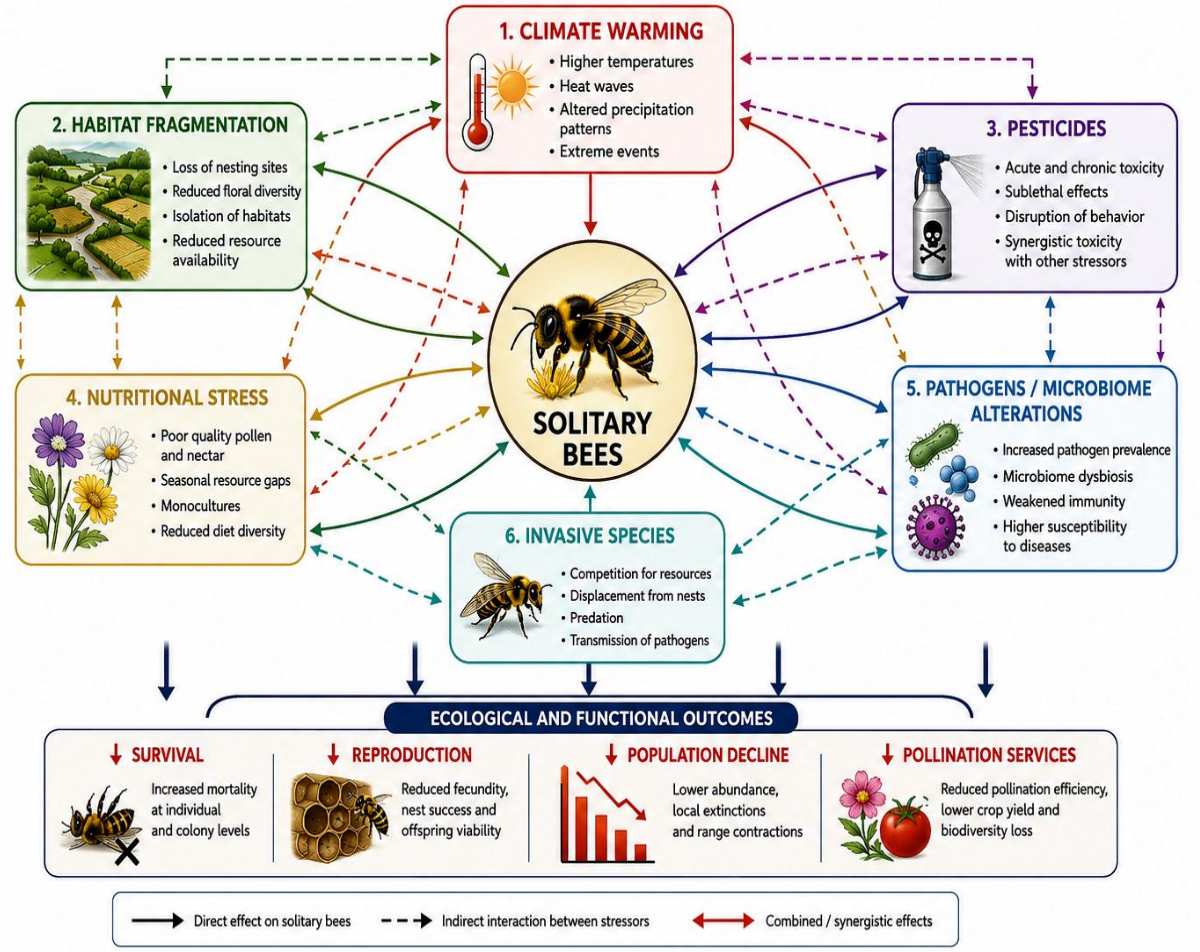


Figure S2. Multiple interacting stressors affecting solitary bee populations and their ecological outcomes. Climate warming, habitat fragmentation, pesticide exposure, nutritional stress, pathogen and microbiome alterations, and invasive species act individually and synergistically to reduce survival, reproduction, and population persistence, leading to declines in pollination services and ecosystem functioning.

Table 3. Multi-stressor interactions affecting solitary bees

Stressor combination	Mechanism	Consequence	Evidence
Heat + nutritional stress	Increased metabolism	Reduced fecundity	Filipiak (2024)
Heat + pesticides	Oxidative stress	Reduced survival	Tosi et al. (2022)
Habitat loss + climate change	Reduced dispersal	Population decline	Harrison et al. (2022)
Climate change + invasive species	Competition	Community restructuring	Zattara and Aizen (2021)

Climate-Resilient Conservation Strategies for Solitary Bees

The conservation of solitary bees has become increasingly important in response to widespread declines driven by habitat degradation, agricultural intensification, pesticide exposure, and climate change (Kennedy et al., 2019; Dicks et al., 2021) (Fig. 3). These pressures frequently interact, amplifying impacts on bee populations and reducing the reliability of pollination services. Effective conservation therefore requires coordinated, multi-scale approaches that address multiple environmental drivers across spatial and ecological gradients (Fahrig et al., 2015). Recent studies emphasize the need to move beyond isolated interventions toward systems-based and nature-based solutions that integrate habitat restoration, landscape heterogeneity, and sustainable agricultural practices (Kremen et al., 2021; Dainese et al., 2019). In agroecosystems, ecological intensification through crop diversification, maintenance of semi-natural habitats, and reduced chemical inputs can simultaneously support biodiversity and agricultural productivity (Garibaldi et al., 2021; Sutter et al., 2024). Increasing evidence also highlights the importance of adaptive management, habitat connectivity, and microclimatic refugia in buffering pollinator populations against environmental variability (Harrison et al., 2022).

Habitat Restoration
Habitat restoration is a cornerstone strategy for conserving solitary bees in intensively managed agroecosystems where resource limitation constrains pollinator populations. Establishment of wildflower strips and restoration of semi-natural habitats consistently increase bee abundance, species richness, and pollination services (Haaland et al., 2011; Kremen et al., 2021). These interventions enhance both the spatial availability and temporal continuity of floral resources, thereby supporting sustained foraging and reducing seasonal resource gaps (Sutter et al., 2024; Albrecht et al., 2023).
Beyond resource quantity, nutritional quality and functional diversity are critical determinants of bee health and population performance. Diverse pollen sources provide essential macro- and micronutrients that improve larval development, immunity, and adult longevity (Vaudo et al., 2015; Wood et al., 2015). Plant species richness and trait diversity further influence pollen nutritional balance and reproductive success under environmental stress (Filipiak, 2024; Drossart et al., 2024). Consequently, restoration programmes should prioritize native and functionally diverse plant assemblages with staggered flowering phenologies to ensure continuous and nutritionally balanced resource availability.

Nesting Resource Management
In addition to foraging resources, nesting habitat availability is a major determinant of solitary bee population viability and reproductive success. Many species exhibit specific nesting requirements; ground-nesting taxa depend on well-drained, sparsely vegetated soils, whereas cavity-nesting species use hollow stems, dead wood, crevices, or artificial substrates (Harmon-Threatt, 2020; Orr et al., 2022). These requirements are closely linked to life-history traits and strongly influence community composition and functional diversity (Orr et al., 2022; Fortel et al., 2021). Incorporating nesting resources into conservation planning can substantially enhance reproductive output, nesting success, and local population persistence (Fortel et al., 2021; MacIvor et al., 2022). In agroecosystems, maintaining bare ground, preserving dead wood, and managing field margins and hedgerows can improve nesting opportunities
(Harmon-Threatt, 2020). Artificial nesting structures may supplement resources in habitat-limited environments; however, their effectiveness depends on appropriate design and maintenance because poorly managed structures can increase parasitism, disease transmission, and competition (MacIvor et al., 2022; Orr et al., 2022; Fortel et al., 2021). Effective conservation requires spatial and temporal alignment of nesting and floral resources because mismatches between the two may constrain population growth (Zurbuchen et al., 2004; Kennedy et al., 2019). Integrating natural nesting habitat restoration with targeted deployment of artificial structures is therefore essential for sustaining populations under land-use and climate pressures (Harrison et al., 2022; Fahrig et al., 2015).

Urban Conservation
Urban ecosystems can function as important refuges for solitary bees, particularly where agricultural intensification has reduced pollinator diversity. Urban green infrastructure, including parks, gardens, roadside verges, and green roofs, can support diverse pollinator communities by providing heterogeneous floral and nesting resources (Baldock et al., 2020; Hall et al., 2017). In some cases, urban environments sustain higher pollinator diversity than surrounding agricultural landscapes because of reduced pesticide use and increased habitat heterogeneity (Baldock et al., 2020; Theodorou et al., 2020). Urban habitats may also act as microclimatic refugia by buffering bees against extreme temperatures through shaded and irrigated environments (Hall et al., 2017; Hamblin et al., 2023). However, the distribution and quality of urban green spaces are often uneven and influenced by socio-economic factors, creating disparities in pollinator diversity and conservation outcomes (Leong et al., 2025). Effective urban conservation therefore requires integration of ecological design with urban planning and governance. Increasing native plant diversity, reducing mowing frequency, limiting pesticide use, and improving connectivity among green spaces can substantially enhance habitat suitability (Hall et al., 2017; Theodorou et al., 2020).

Genetic and Functional Diversity
Maintaining genetic diversity is essential for the adaptive capacity and long-term persistence of solitary bee populations under environmental change. High genetic variability facilitates responses to climate change, habitat fragmentation, and pesticide exposure, whereas reduced diversity increases extinction risk (López-Uribe et al., 2023; Harrison et al., 2022). Habitat fragmentation and population isolation in agroecosystems can further erode genetic diversity by limiting gene flow and increasing inbreeding. Conserving functional diversity is equally important for sustaining ecosystem processes and pollination services. Trait-based approaches emphasize preserving variation in body size, foraging range, phenology, and nesting behaviour, which determine both species responses and ecosystem contributions (Bartomeus et al., 2023). Functionally diverse communities enhance pollination efficiency, provide ecological redundancy, and buffer ecosystem services against environmental fluctuations and species loss (Dainese et al., 2019; Albrecht et al., 2023). Integrating genetic and functional perspectives therefore improves predictions of species resilience and ecosystem stability under global change and should be considered a central component of climate-resilient pollinator conservation.

Climate Change and Solitary Bees in Tropical Agroecosystems

Importance of Tropical Agroecosystems for Solitary Bee Diversity

Tropical regions harbour exceptionally high pollinator diversity and support numerous crop species that depend partially or entirely on animal-mediated pollination (Potts et al., 2016). Solitary bees constitute an important component of these pollinator communities and contribute substantially to the production of tropical fruits, vegetables, spices, oilseeds, and plantation crops (Garibaldi et al., 2013). Crops such as mango, cashew, coffee, cocoa, pigeon pea, cucurbits, tomato, chilli, and sesame benefit significantly from pollination services provided by wild solitary bees and other native pollinators (Freitas et al., 2009). Tropical agroecosystems are characterized by high habitat heterogeneity, prolonged flowering periods, and complex plant–pollinator interactions that support rich assemblages of solitary bee species. Consequently, these ecosystems represent both major reservoirs of pollinator diversity and important providers of ecosystem services that underpin food security and rural livelihoods.

Climate Change Impacts in Tropical Regions

Tropical regions are expected to experience increasing temperatures, altered precipitation regimes, prolonged droughts, and more frequent extreme weather events during the twenty-first century (IPCC, 2023). These changes are likely to have profound consequences for solitary bee populations because many tropical species already occur near their upper thermal limits (Deutsch et al., 2008; Hamblin et al., 2023). Elevated temperatures may reduce adult longevity, impair foraging behaviour, alter developmental rates, and decrease reproductive success. Changes in precipitation and increasing drought frequency can further reduce floral resource availability and alter pollen nutritional quality, thereby affecting larval development and population growth (Hoover et al., 2024; Filipiak, 2024). Extreme rainfall events may destroy nests of ground-nesting species and reduce brood survival, particularly in seasonally dry tropical environments (Harrison et al., 2022). Because many tropical pollinator communities remain poorly studied, considerable uncertainty exists regarding their adaptive capacity and resilience under future climate scenarios.

Tropical Crops and Pollination Services

Pollinator-dependent crops are disproportionately concentrated in tropical regions and contribute significantly to food security, nutritional diversity, and rural livelihoods (Potts et al., 2016). Solitary bees are particularly important pollinators of several tropical crops because of their behavioural specialization, floral constancy, and high pollination efficiency (Garibaldi et al., 2013). Consequently, climate-induced declines in pollinator populations may have substantial ecological, economic, and social consequences, particularly in developing countries where agricultural production and livelihoods depend heavily on ecosystem services (Aizen et al., 2009; IPBES, 2016).

Climate-Resilient Conservation Strategies for Tropical Agroecosystems

Conservation strategies in tropical agroecosystems should prioritize:

- preservation of native vegetation and forest fragments;
- maintenance of floral and nesting resources;
- crop diversification and agroforestry systems;
- reduction of pesticide inputs through ecological intensification;
- enhancement of habitat connectivity; and
- community-based pollinator conservation programmes.

Agroforestry systems and diversified farming landscapes support higher pollinator diversity and provide greater resilience to climatic disturbances than simplified monocultures (Kremen and M'Gonigle, 2015). Integrating pollinator conservation into climate-smart agriculture is therefore essential for maintaining ecosystem services, agricultural productivity, and food security in tropical regions.

Pesticide Risk Mitigation

Pesticide exposure remains one of the major threats to solitary bees, with many species showing greater sensitivity to agrochemicals than managed honey bees under field-realistic conditions (Arena and Sgolastra, 2020). In addition to acute toxicity, sublethal effects such as impaired navigation, reduced foraging efficiency, altered behaviour, and decreased reproduction can have cascading impacts on individual fitness and population dynamics (Tosi et al., 2017). These effects are frequently intensified by chronic exposure and interactions with other environmental stressors, including nutritional limitation and thermal stress, emphasizing the importance of evaluating pesticide impacts within a multi-stressor framework (Goulson et al., 2015). Reducing pesticide reliance through integrated pest management (IPM) should therefore be a central component of climate-resilient pollinator conservation. Strategies including biological control, crop diversification, resistant varieties, and ecological intensification can reduce pesticide inputs while maintaining agricultural productivity (Dicks et al., 2021). Additional measures, including pesticide-free buffer zones, optimized application timing, and the selection of less toxic compounds, can further reduce exposure risks (Tosi et al., 2017). Moreover, risk assessment frameworks should incorporate mixture toxicity and cumulative exposure because bees are generally exposed to multiple compounds rather than individual chemicals (Alix et al., 2022). Advancing pesticide-risk mitigation requires improved regulatory frameworks and field-realistic testing protocols that account for species-specific sensitivity, life-history traits, and sublethal endpoints. Integrating these approaches within agroecological production systems is essential to reduce chemical inputs while sustaining pollination services and enhancing the resilience of solitary bee populations under ongoing environmental change

Supporting Conservation Planning and Monitoring

Combining information from eDNA, remote sensing, automated monitoring, and long-term ecological datasets provides powerful tools for conservation planning and assessment of climate-change impacts on solitary bees and pollination services (Richardson et al., 2025; Thuiller et al., 2019). These approaches can be used to identify vulnerable species and populations; to locate climate refugia; to evaluate habitat connectivity; prioritize conservation actions; and assess future risks under alternative climate and land-use scenarios.

Advances in machine learning and species-distribution modelling further improve the capacity to analyse complex interactions among climatic, ecological, and anthropogenic drivers (Hartig et al., 2024; Araújo et al., 2019). Emerging monitoring tools, including sensor networks, automated imaging systems, and acoustic monitoring, also enable near real-time assessment of pollinator activity, species composition, and habitat use (Høye et al., 2025). These technologies facilitate evaluation of conservation interventions, including habitat restoration, enhancement of floral and nesting resources, and pesticide-risk mitigation. By integrating ecological monitoring with predictive analytics, these approaches support adaptive management and evidence-based conservation planning under rapidly changing environmental conditions.

Research Gaps and Future Directions

Despite considerable progress, significant knowledge gaps remain in understanding solitary bee-mediated pollination across biogeographic regions, particularly in tropical and other underrepresented ecosystems (Bartomeus et al., 2023). Current research is heavily concentrated in Europe and North America, limiting the generality of existing knowledge in regions that harbour the greatest diversity of solitary bees (Dainese et al., 2019). Furthermore, studies have focused disproportionately on a few model genera, such as *Osmia* and *Megachile*, whereas the ecology, functional significance, and climate sensitivities of most solitary bee taxa remain poorly understood (Drossart et al., 2024; Orr et al., 2022).

Another major limitation is the incomplete understanding of how functional traits mediate species responses to interacting environmental stressors. Traits such as body size, phenology, nesting strategy, foraging range, and dietary specialization strongly influence vulnerability and resilience, yet their interactions with climate change, land-use intensification, and pesticide exposure remain insufficiently resolved (Garibaldi et al., 2021; Garratt et al., 2023; Wood et al., 2015; Van der Sluijs et al., 2023). Addressing these uncertainties requires mechanistic, trait-based approaches that explicitly link environmental drivers with ecological functions across spatial and temporal scales (Bartomeus et al., 2023). The scarcity of long-term and standardized datasets on solitary bee populations, community dynamics, and pollination services further constrains the detection of temporal trends and the prediction of responses to environmental change (Wagner, 2020). Establishing coordinated monitoring networks and harmonized protocols, supported by emerging technologies such as remote sensing, automated monitoring systems, and environmental DNA, will substantially improve data coverage and predictive capacity (Høye et al., 2025; Deiner et al., 2017). Future research should increasingly integrate field experiments, long-term monitoring, landscape-scale analyses, and predictive modelling to better quantify pollination services and ecosystem resilience (Albrecht et al., 2023; Thuiller et al., 2019).

From an applied perspective, greater emphasis should be placed on developing and evaluating climate-resilient, biodiversity-friendly agricultural practices that enhance solitary bee populations and pollination services (Sutter et al., 2024). Habitat restoration, crop diversification, enhancement of nesting resources, and reduction of pesticide risks should be assessed across diverse agroecological contexts to optimize conservation outcomes (Garibaldi et al., 2021; Albrecht et al., 2023). Integrating these approaches into land-use planning, agricultural policies, and conservation programmes will be essential for sustaining biodiversity, ecosystem functioning, and food security under global environmental change (Van der Sluijs et al., 2023; Kremen et al., 2021).

Collectively, these research gaps highlight the need for a more integrative understanding of how climate drivers, physiological mechanisms, ecological interactions, and anthropogenic pressures shape solitary bee populations and pollination services.

CONCLUSIONS

Solitary bees are among the most diverse and functionally important wild pollinators, contributing substantially to biodiversity conservation, ecosystem functioning, and agricultural productivity. Animal-mediated pollination contributes an estimated USD 235–577 billion annually to global agriculture, highlighting the critical importance of pollinators in sustaining food production systems. Owing to their high per-visit efficiency and functional diversity, solitary bees play a disproportionate role in maintaining pollination services and enhancing agroecosystem resilience under environmental variability (Garibaldi et al., 2021). Conserving solitary bee diversity is therefore both an ecological priority and an economic necessity.

Enhancing pollinator resilience will require integrated conservation strategies that combine habitat restoration, diversification of landscapes, enhancement of floral and nesting resources, ecological intensification, and pesticide-risk mitigation. Particular attention should be directed toward tropical agroecosystems, which support exceptional pollinator diversity but remain underrepresented in climate-change research. Emerging technologies, including environmental DNA, remote sensing, artificial intelligence, automated monitoring, and ecological forecasting, offer unprecedented opportunities to improve monitoring, predictive modelling, and adaptive conservation planning.

The Climate-Resilient Solitary Bee Conservation Framework (CRSBCF) proposed here provides a systems-based approach that integrates climate drivers, multi-stressor interactions, biological responses, ecosystem services, conservation interventions, and technological innovations. By linking ecological processes with adaptive management and policy actions, the framework offers a conceptual foundation for future research and evidence-based conservation planning across diverse agroecosystems.

Future efforts should prioritize long-term monitoring programmes, multi-stressor experiments, trait-based ecological modelling, and expanded research in tropical and other underrepresented regions. Strengthening the integration of science, policy, and land management will be essential for conserving solitary bee diversity and sustaining the pollination services that underpin ecosystem stability, agricultural resilience, and global food security in an increasingly uncertain climate.

REFERENCES

1. Albrecht, M., Kleijn, D., Williams, N.M., Tschumi, M., Blaauw, B.R. and colleagues. (2023). The effectiveness of flower strips and semi-natural habitats for pollinator conservation and ecosystem services. Annual Review of Ecology, Evolution, and Systematics 54, 177–203.

2. Alex, A.J., Barnes, C.M., Machado, P., Ihianle, I., Markó, G., Bencsik, M. and Bird, J.J. (2024). Enhancing pollinator conservation towards Agriculture 4.0: Monitoring of bees through object recognition. Smart Agricultural Technology 8, 100486. https://doi.org/10.1016/j.atech.2024.100486

3. Alix, A., Zucchi, M.I., Sgolastra, F. and colleagues. (2022). Lethal, sublethal, and combined effects of pesticides on bees: A review and new datasets for risk assessment. Science of the Total Environment 844, 156857. https://doi.org/10.1016/j.scitotenv.2022.156857

4. Alves-dos-Santos, I. (2025). Global change and pollinator conservation: The need for multi-stressor approaches. Current Opinion in Insect Science 67, 101233. https://doi.org/10.1016/j.cois.2025.101233

5. Araújo, M.B., Anderson, R.P., Barbosa, A.M., Beale, C.M., Dormann, C.F. and colleagues. (2019). Standards for distribution models in biodiversity assessments. Science Advances 5, eaat4858. https://doi.org/10.1126/sciadv.aat4858

6. Arena, M. and Sgolastra, F. (2020). A meta-analysis comparing the sensitivity of bees to pesticides. Ecotoxicology 29, 1235–1254.

7. Avalos, G., Paniw, M. and Saavedra, S. (2024). Climate change, ecological networks and the future of pollination services. Trends in Ecology and Evolution 39, 565–578. https://doi.org/10.1016/j.tree.2024.02.006

8. Baldock, K.C.R., Goddard, M.A., Hicks, D.M., Kunin, W.E., Mitschunas, N. and colleagues. (2020). A systems approach reveals urban pollinator hotspots and conservation opportunities. Nature Ecology and Evolution 4, 363–373. https://doi.org/10.1038/s41559-020-1117-6

9. Bartomeus, I., Molina, F.P., Hidalgo-Galiana, A. and Saavedra, S. (2021). Climate-associated phenological advances in bee pollinators and their effects on plant–pollinator interactions. Proceedings of the Royal Society B 288, 20202961. https://doi.org/10.1098/rspb.2020.2961

10. Bosch, J. and Kemp, W.P. (2002). Developing Osmia spp. as crop pollinators. Bulletin of Entomological Research 92, 3–16.

11. Bosch, J. and Kemp, W.P. (2004). Wintering effects in Osmia cornuta. Apidologie 35, 469–479.

12. Bosch, J., Sgolastra, F. and Kemp, W.P. (2010). Life-cycle ecophysiology of Osmia bees. IOBC/WPRS Bulletin 57, 83–90.

13. Bosch, J. and Vicens, N. (2006). Body size and reproductive success in Osmia cornuta. Behavioral Ecology and Sociobiology 60, 26–33. https://doi.org/10.1007/s00265-005-0134-4

14. CaraDonna, P.J., Cunningham, J.L. and Iler, A.M. (2014). Experimental warming in the field delays phenology and reduces body mass, fat content and survival: Implications for pollinator responses to climate change. Functional Ecology 28, 1062–1072. https://doi.org/10.1111/1365-2435.12257

15. CaraDonna, P.J., Iler, A.M. and Inouye, D.W. (2021). Shifts in flowering phenology reshape a subalpine plant–pollinator network. Proceedings of the National Academy of Sciences of the United States of America 118, e2100389118. https://doi.org/10.1073/pnas.2100389118

16. Chapuisat, M. (2010). Plastic sociality in a primitively eusocial bee. Current Biology 20, R977–R979. https://doi.org/10.1016/j.cub.2010.10.033

17. Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A. and colleagues. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. Science Advances 5, eaax0121. https://doi.org/10.1126/sciadv.aax0121.

18. De Manincor, N., Fisogni, A. and Rafferty, N.E. (2023). Warming alters pollinator interactions and reshapes plant–pollinator networks. Ecology Letters 26, 323–334.

19. Descamps, C., Quinet, M., Baijot, A. and Jacquemart, A.L. (2021). Temperature and water stress affect plant–pollinator interactions and consequences for pollination and plant reproduction. Frontiers in Plant Science 12, 714678. https://doi.org/10.3389/fpls.2021.714678
20. Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. and Martin, P.R. (2008). Impacts of climate warming on terrestrial ectotherms across latitude. Proceedings of the National Academy of Sciences of the United States of America 105, 6668–6672. https://doi.org/10.1073/pnas.0709472105
21. Dicks, L.V., Breeze, T.D., Ngo, H.T., Senapathi, D., An, J., Aizen, M.A., Basu, P., Buchori, D., Galetto, L., Garibaldi, L.A. and colleagues. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. Nature Ecology and Evolution 5, 1453–1461. https://doi.org/10.1038/s41559-021-01534-9
22. Drossart, M., Michez, D., Vanderplanck, M. and colleagues. (2024). Functional traits of wild bees and their implications for pollination services under environmental change. Biological Reviews 99, 502–523. https://doi.org/10.1111/brv.13035
23. Engel, P. and Moran, N.A. (2013). The gut microbiota of insects – diversity in structure and function. FEMS Microbiology Reviews 37, 699–735.
24. Fahrig, L., Girard, J., Duro, D., Pasher, J., Smith, A., Javorek, S., King, D., Lindsay, K.F., Mitchell, S. and Tischendorf, L. (2015). Farmlands with smaller crop fields have higher within-field biodiversity. Agriculture, Ecosystems and Environment 200, 219–234. https://doi.org/10.1016/j.agee.2014.11.018
25. Field, J., Paxton, R.J., Soro, A. and Bridge, C. (2012). Body size, demography and foraging behaviour in socially polymorphic sweat bees. Behavioral Ecology and Sociobiology 66, 743–756.
26. Filipiak, M. (2024). Nutritional ecology of bees in a changing world: Consequences of altered pollen quality for pollinator health and ecosystem functioning. Current Opinion in Insect Science 63, 101173. https://doi.org/10.1016/j.cois.2024.101173
27. Forrest, J.R.K. (2015). Plant–pollinator interactions and phenological change: What can we learn about climate impacts from experiments and observations? Oikos 124, 4–13.
28. Forrest, J.R.K. (2021). Climate change and the ecology of pollination. Current Opinion in Insect Science 47, 135–142.
29. Fortel, L., Henry, M., Guilbaud, L., Mouret, H. and Vaissière, B.E. (2021). Use of human-made nesting structures by wild bees in urban environments. Journal of Applied Ecology 58, 1045–1057. https://doi.org/10.1111/1365-2664.13836
30. Freitas, B.M., Imperatriz-Fonseca, V.L., Medina, L.M., Kleinert, A.M.P., Galetto, L., Nates-Parra, G. and Quezada-Euán, J.J.G. (2009). Diversity, threats and conservation of native bees in the Neotropics. Apidologie 40, 332–346. https://doi.org/10.1051/apido/2009012
31. Garibaldi, L.A., Oddi, F.J., Miguez, F.E., Bartomeus, I., Orr, M.C., Jobbágy, E.G., Kremen, C., Schulte, L.A., Hughes, A.C. and colleagues. (2021). Working landscapes need at least 20% native habitat. Conservation Letters 14, e12773. https://doi.org/10.1111/conl.12773
32. Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O. and colleagues. (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 339, 1608–1611. https://doi.org/10.1126/science.1230200
33. Garratt, M.P.D., Bishop, J., Degani, E., Potts, S.G., Shaw, R.F., Shi, A., Roy, S., Yates, G.W. and colleagues. (2023). Contributions of wild bees to crop pollination, yield and quality under global change. Annual Review of Ecology, Evolution, and Systematics 54, 389–412. https://doi.org/10.1146/annurev-ecolsys-102221-050319
34. Ghisbain, G., Lozier, J.D., Rahman, S.R., Ezray, B.D., Tian, L., Ulmer, J.M. and Strange, J.P. (2020). Substantial genetic divergence and lack of recent gene flow support cryptic speciation in a bumble bee under climate change. Molecular Ecology 29, 1725–1738. https://doi.org/10.1111/mec.15414.
35. Goulson, D., Nicholls, E., Botías, C. and Rotheray, E.L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347, 1255957. https://doi.org/10.1126/science.1255957
36. Haaland, C., Naisbit, R.E. and Bersier, L.F. (2011). Sown wildflower strips for insect conservation: A review. Insect Conservation and Diversity 4, 60–80. https://doi.org/10.1111/j.1752-4598.2010.00098.x
37. Haddaway, N.R., Collins, A.M., Coughlin, D. and Kirk, S. (2015). The role of Google Scholar in evidence reviews and its applicability to grey literature searching. PLoS ONE 10, e0138237. https://doi.org/10.1371/journal.pone.0138237
38. Hall, D.M., Camilo, G.R., Tonietto, R.K., Ollerton, J., Ahrné, K., Arduser, M., Ascher, J.S., Baldock, K.C.R., Fowler, R., Frankie, G. and colleagues. (2017). The city as a refuge for insect pollinators. Conservation Biology 31, 24–29. https://doi.org/10.1111/cobi.12840
39. Hamblin, A.L., Youngsteadt, E., López-Uribe, M.M. and Frank, S.D. (2023). Physiological and ecological responses of bees to urban heat and climate warming. Current Opinion in Insect Science 58, 101047. https://doi.org/10.1016/j.cois.2023.101047
40. Hammer, T.J., Le, E., Martin, A.N. and Moran, N.A. (2021). The gut microbiota of bees: Biodiversity, function, and vulnerability to environmental change. Annual Review of Entomology 66, 165–185. https://doi.org/10.1146/annurev-ento-120920-013741
41. Harmon-Threatt, A.N. (2020). Influence of nesting characteristics on health of wild bee communities. Annual Review of Entomology 65, 39–56.

42. Hartig, F., Calabrese, J.M., Reineking, B., Wiegand, T. and Huth, A. (2024). Machine learning and ecological forecasting for biodiversity conservation under global change. Trends in Ecology and Evolution 39, 313–326. https://doi.org/10.1016/j.tree.2023.11.004
43. Hayes, T. and López-Martínez, G. (2021). Heat stress in solitary bees: Implications for survival and reproduction. Current Research in Insect Science 1, 100020. https://doi.org/10.1016/j.cris.2021.100020
44. Herrera, C.M., Núñez, A. and Valverde, J. (2023). Declining body mass in wild bees under contemporary climate change. Ecology 105, e4128. https://doi.org/10.1002/ecy.4128
45. Herrera, C.M., Medrano, M. and Bazaga, P. (2024). Climate warming reshapes pollinator communities and pollination services: Emerging evidence from long-term studies. Global Change Biology 30, e17249. https://doi.org/10.1111/gcb.17249
46. Hoover, S.E.R., Ladley, J.J., Shchepetkina, A.A., Tisch, M., Gieseg, S.P. and Tylianakis, J.M. (2024). Warming alters pollen nutritional quality and consequences for bee health and pollination services. Current Opinion in Insect Science 63, 101172. https://doi.org/10.1016/j.cois.2024.101172
47. Høye, T.T., Loboda, S., Koltz, A.M., Gillespie, M.A.K. and Bowden, J.J. (2025). Automated biodiversity monitoring in the era of artificial intelligence and ecological forecasting. Trends in Ecology and Evolution 40, 85–99. https://doi.org/10.1016/j.tree.2024.08.005
48. IPBES. (2016). The Assessment Report on Pollinators, Pollination and Food Production. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. https://doi.org/10.5281/zenodo.3402856
49. IPCC. (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647
50. Jha, S., Kremen, C. and colleagues. (2024). Climate-smart pollinator conservation in agricultural landscapes. Annual Review of Environment and Resources 49, 321–348. https://doi.org/10.1146/annurev-environ-112321-095028
51. Kennedy, C.M., Hawthorne, P.L., Miteva, D.A., Baumgarten, L., Sochi, K., Matsumoto, M., Evans, J.S., Polasky, S., Hamel, P. and Vieira, E.M. (2019). Managing the middle: A shift in conservation priorities based on the global human modification gradient. Global Change Biology 25, 811–826. https://doi.org/10.1111/gcb.14549
52. Kremen, C., Albrecht, M. and Ponisio, L.C. (2021). Restoring pollinator communities and pollination services in agricultural landscapes. Current Opinion in Insect Science 45, 100932. https://doi.org/10.1016/j.cois.2021.100932
53. Kremen, C., M'Gonigle, L. K., & Ponisio, L. C. (2018). Pollinator community assembly tracks changes in floral resources as restored hedgerows mature in agricultural landscapes. *Frontiers in Ecology and Evolution*, *6*, 170. https://doi.org/10.3389/fevo.2018.00170
54. Kudo, G. and Cooper, E.J. (2019). When spring ephemerals fail to meet pollinators: Mechanisms of phenological mismatch and its consequences. Proceedings of the Royal Society B 286, 20190573. https://doi.org/10.1098/rspb.2019.0573
55. Kudo, G. and Ida, T.Y. (2013). Early onset of spring increases the phenological mismatch between plants and pollinators. Ecology 94, 2311–2320.
56. Kunjwal, N., Khan, M.S., Kumar, G. and Srivastava, P. (2020). Nesting ecology and trap-nesting behaviour of Megachile species in the Indian Himalaya. Journal of Apicultural Research 60, 807–816.
57. Leong, M., Ponisio, L.C. and Kremen, C. (2025). Urbanization, environmental justice and pollinator conservation in changing landscapes. Annual Review of Ecology, Evolution, and Systematics 56, 157–180. https://doi.org/10.1146/annurev-ecolsys-112223-101420
58. López-Uribe, M.M., Jha, S. and Gibbs, J. (2023). Conserving genetic diversity in wild bees under climate and land-use change. Annual Review of Entomology 68, 237–256. https://doi.org/10.1146/annurev-ento-120220-093352
59. MacIvor, J. S., de Keyzer, C. W., Marshall, M. S., Thurston, G. S., & Onuferko, T. M. (2022). Establishment of the non-native horned-face bee Osmia cornifrons and the taurus mason bee Osmia taurus (Hymenoptera: Megachilidae) in Canada. *PeerJ*, *10*, e14216.
60. Martins, K.T., Gonzalez, A. and Lechowicz, M.J. (2024). Thermal performance and vulnerability of pollinators under climate change. Biological Reviews 99, 612–631. https://doi.org/10.1111/brv.13052
61. Melone, G.G., Stuligross, C. and Williams, N.M. (2024). Heatwaves affect bee activity, survival and pollination services. Ecological Entomology 49, 433–444. https://doi.org/10.1111/een.13240
62. Melone, F., Hayes, J.L. and López-Martínez, G. (2024). Heat stress and thermal plasticity in solitary bees: Implications for pollinator persistence under climate change. Current Opinion in Insect Science 63, 101176. https://doi.org/10.1016/j.cois.2024.101176
63. Michener, C.D. (2000). The Bees of the World. Johns Hopkins University Press, Baltimore, MD, USA.
64. Michener, C.D. (2007). The Bees of the World, 2nd edn. Johns Hopkins University Press, Baltimore, MD, USA.
65. Orr, M. C., Jakob, M., Harmon-Threatt, A., & Mupepele, A. C. (2022). A review of global trends in the study types used to investigate bee nesting biology. *Basic and Applied Ecology*, *62*, 12-21.

66. Pocock, M.J.O., Tweddle, J.C., Savage, J., Robinson, L.D. and Roy, H.E. (2017). The diversity and evolution of ecological and environmental citizen science. PLoS ONE 12, e0172579. https://doi.org/10.1371/journal.pone.0172579
67. Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T., Aizen, M.A., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J. and Vanbergen, A.J. (2016). Safeguarding pollinators and their values to human well-being. Nature 540, 220–229.
68. Quaresma, A., Gérard, M., Michez, D. and Vanderplanck, M. (2025). Drought-mediated changes in floral resources and consequences for bee nutrition and pollination services. Current Opinion in Insect Science 67, 101239. https://doi.org/10.1016/j.cois.2025.101239
69. Radzevičiūtė, R., Theodorou, P., Schlegel, M., & Paxton, R. J. (2021). A two-part modelling approach reveals a positive effect of pollinator biodiversity in boosting the pollination of apple flowers. *Agriculture, ecosystems & environment*, *306*, 107197.
70. Richardson, L.L., McArt, S.H., Russo, L. and colleagues. (2025). Long-term ecological monitoring and forecasting of pollinator populations under global change. Annual Review of Ecology, Evolution, and Systematics 56, 335–360. https://doi.org/10.1146/annurev-ecolsys-112223-103842
71. Sgolastra, F., Arnan, X., Cabbri, R., Isani, G., Medrzycki, P., Teper, D. and Bosch, J. (2016). Combined exposure to sublethal concentrations of an insecticide and high temperature increases mortality in solitary bees. Ecological Entomology 41, 201–210.
72. Slominski, A.H. and Burkle, L.A. (2019). Temperature effects on pollinator performance and plant–pollinator interactions. Frontiers in Ecology and Evolution 7, 314. https://doi.org/10.3389/fevo.2019.00314
73. Slominski, D. and Burkle, L.A. (2019). Climate change and pollinator communities: Shifts in species distributions, assemblages, and interactions. Current Climate Change Reports 5, 115–130. https://doi.org/10.1007/s40641-019-00136-x
74. Sutter, L., Jeanneret, P., Bartual, A.M., Bocci, G., Albrecht, M. and colleagues. (2024). Ecological intensification promotes pollinators and pollination services in agricultural landscapes. Nature Ecology and Evolution 8, 342–352. https://doi.org/10.1038/s41559-023-02242-8
75. Theodorou, P., Radzevičiūtė, R., Lentendu, G., Kahnt, B., Husemann, M. and colleagues. (2020). Urban areas as hotspots for bees and pollination but not a panacea for all insects. Nature Communications 11, 576. https://doi.org/10.1038/s41467-020-14496-6
76. Thuiller, W., Guéguen, M., Renaud, J., Karger, D.N. and Zimmermann, N.E. (2019). Uncertainty in ensembles of global biodiversity scenarios. Nature Communications 10, 1446. https://doi.org/10.1038/s41467-019-09519-w
77. Tosi, S., Nieh, J.C., Sgolastra, F., Cabbri, R. and Medrzycki, P. (2017). Neonicotinoid pesticides and nutritional stress synergistically reduce survival in bees. Proceedings of the Royal Society B 284, 20171711. https://doi.org/10.1098/rspb.2017.1711
78. Van der Sluijs, J.P., Vaage, N.S., Arild, M. and colleagues. (2023). Pollinator decline and food security: The need for transformative change. Current Opinion in Environmental Sustainability 62, 101280. https://doi.org/10.1016/j.cosust.2023.101280
79. Vaudo, A.D., Tooker, J.F., Grozinger, C.M. and Patch, H.M. (2015). Bee nutrition and floral resource restoration. Current Opinion in Insect Science 10, 133–141. https://doi.org/10.1016/j.cois.2015.05.008
80. Wagner, D.L. (2020). Insect declines in the Anthropocene. Annual Review of Entomology 65, 457–480.
81. Wood, T.J., Holland, J.M. and Goulson, D. (2015). Pollinator-friendly management does not increase the diversity of farmland bees and wasps. Biological Conservation 187, 120–126. https://doi.org/10.1016/j.biocon.2015.04.022
82. Zattara, E.E. and Aizen, M.A. (2021). Worldwide occurrence records suggest a global decline in bee species richness. One Earth 4, 114–123.
83. Zurbuchen, A., Landert, L., Klaiber, J., Müller, A., Hein, S. and Dorn, S. (2004). Maximum foraging ranges in solitary bees: Implications for habitat management and conservation. Biological Conservation 118, 589–596.