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REVIEW

Global Pollinator Declines in the Anthropocene: Climate Change, Agriculture, and Food Security

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ABSTRACT

Global pollinator populations are declining owing to climate shifts and agricultural expansion, threatening ecosystem stability, crop production, and food security. This review synthesizes empirical findings across diverse pollinator taxa, showing that increased temperature, altered precipitation, and extreme climatic events affect abundance, phenology, and distribution. Industrial farming intensifies these declines by fragmenting habitats and exposing pollinators to pesticides, thereby impairing the pollination of both wild plants and crops. Meta-analyses have revealed that reductions in pollinator diversity reduce the yield and nutritional quality of pollinator-dependent crops. A quantitative synthesis of 89 studies (1950–2023) highlights that climatic variability strongly impacts pollination

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processes in tropical regions, where reliance on wild pollinators and narrow thermal tolerances limit species' adaptive capacity. This creates a "pollination-nutrition-health nexus" that links biodiversity loss to human dietary health. Despite the growing data from temperate regions, knowledge gaps persist in tropical ecosystems and non-bee pollinators. This review identifies five key priorities: (1) scaling standardized monitoring in underserved regions, (2) integrating ecological and socio-economic data, (3) employing trait- and network-based resilience metrics, (4) embedding pollinator conservation in climate policy, and (5) expanding technological and citizen-science approaches. We advocate a systems-oriented framework that unites biodiversity conservation, climate adaptation, and sustainable food systems. Protecting pollinators necessitates pollinator-friendly agriculture, habitat restoration, and the integration of pollination services into environmental management, recognizing pollinators as essential for planetary and human health.

Keywords: Pollinator Decline; Climate Change; Agricultural Intensification; Food Security

1. Introduction

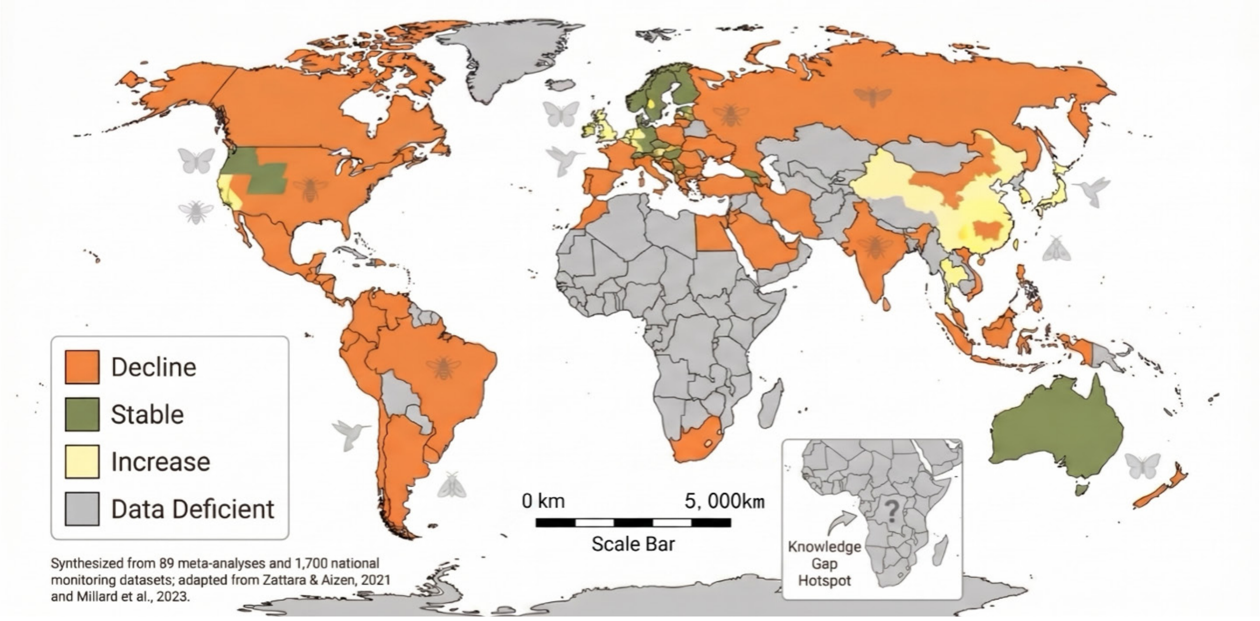
The period of increasing human influence on Earth's ecosystems, biodiversity, and biogeochemical processes has been the subject of thorough scientific study [1]. One telling result of this period is the change to ecosystem services, which are fundamental to human existence. Animal-mediated pollination which vital service to the reproductive processes of most angiosperm species [2,3]. On this basis, pollinators are vital to bridging biodiversity, ecosystem dynamics, and food systems worldwide. Pollinators are taxonomically diverse groups that include several types of insects (bees, butterflies, flies, and beetles), birds (like hummingbirds and sunbirds), bats, and other vertebrates. They have distinct contributions to the reproduction of both wild and cultivated plants. Beyond increasing the quantity of crops available, they also help maintain wild plant communities and the overall genetic diversity and stability of ecosystems [3,4]. About 87% of flowering plant species, and the same proportion of important food crops worldwide, rely, at least in part, on pollinators [3]. Thus, the loss or decline of pollinators is detrimental to ecosystem integrity and human survival.

The last decade has seen significant concern about the decline in the number, diversity, and functional ability of pollinators worldwide [2]. While land-use change, agricultural intensification, pesticide use, invasive species, and disease pathogens have been considered significant stressors for the last several decades [5–7], climate change has more recently been recognized as a unique stressor given its global reach and synergistic, compounding effects with these previous stressors [8]. The ongoing climate includes alterations in temperature, precipitation, the timing of seasonal events, and the spatial patterns of resources. Sustainable agricultural practices and technological innovations are pivotal for addressing climate change challenges, particularly in vulnerable dryland farming systems [8,9]. These regions face compounded stresses from water scarcity, soil salinity, and degradation, which threaten crop productivity and food security [10,11]. Research has demonstrated that nature-based solutions and improved fallow management practices can significantly enhance soil water conservation and alleviate climate change stress [12]. Furthermore, long-term meta-analyses confirm that strategic agronomic practices, including crop rotation and optimized irrigation, substantially improve winter wheat yield, water-use efficiency, and nitrogen-use efficiency in drylands worldwide [13,14]. To combat specific abiotic stresses, studies have shown that the application of silicon can effectively ameliorate the harmful effects of soil salinity on plants [15,16]. At the same time, zinc oxide nanoparticles have been proven to improve chlorophyll content and wheat yield under salt stress [17,18]. Beyond traditional agronomy, technological integration is transformative, with artificial intelligence (AI), internet of things (IoT), and biotechnology playing central roles in precision environmental management and the remediation of contaminated soils [19–22]. Together, these changes have pressured pollinators and their communities, which in turn alter the physiology, behavior, composition, and distribution of pollinating communities. Several studies have documented declines in nectar quality and significant pollinators' activity periods [3]. Given the above, the climate crisis, along with agriculture's reliance on pollinator services, presents a serious threat to pollinators and the services they provide to ecosystems.

Fruits, vegetables, nuts, and seeds depend on pollinators for harvest. With global agricultural intensification, the expansion of pollinator-dependent crop areas and the demand for stable, higher yields make the vulnerability of pollination services more apparent [4]. Additionally, climate change affects not only wild pollinators but also the consistency of pollination within agro-ecosystems. New simulations show that areas suitable for growing pollinator-dependent crops will decrease by more than 10–15% in numerous regions by 2070 under high-emission climate scenarios [23]. Thus, climate change risks, agricultural growth, and pollinator decline are interconnected, calling for a more extensive synthesis.

Through this review, we articulate a component synthesis for four closely interrelated themes: (1) recent trends, distribution, and diversity of pollinator taxa across ecosystems; (2) the role of climate change and pollinator-dependent agriculture in the community structure and service delivery of ecosystem pollinators; (3) the consequences of pollinator decline for the world's food production system and human food security; and (4) emergent pathways for resilience, adaptive management, and policy integration. This review aims to articulate the magnitude of pollinator decline and the nexus among agriculture, climate change, and the global food system, while outlining the mechanisms of risk and pathways to mitigate pollination service decline.

Figure 1 represents global synthesized patterns of change in pollinator abundance, based on meta-analyses and national biodiversity reports. The analysis integrates data from 89 published studies and more than 1,700 national monitoring reports from 1950 to 2023, spanning more than 5,800 species across 75 countries [24,25]. The animal silhouettes (e.g., bees, butterflies, moths, and birds) overlaid on the map illustrate the primary taxonomic groups of pollinators evaluated within these underlying datasets. Orange-shaded regions are areas of the world that have reported declines in the number and diversity of pollinators. These regions often experience aggressive farming and pesticide use coupled with climate stress. Olive-green-shaded regions have pollinator populations that remain neutral (or stable) and are found in areas with strong conservation efforts and/or lower land-use intensity. Light yellow regions show localized increases in pollinator number and diversity. Grey regions are data-poor and are found predominantly in sub-Saharan Africa, Central Asia, and some tropical regions. Overall, the spatial pattern confirms a global decline in pollinator diversity and abundance from the mid-20th century to the present in the Americas, Europe, and most of Asia.



Synthesized from 89 meta-analyses and 1,700 national monitoring datasets; adapted from Zattara & Aizen, 2021 and Millard et al., 2023.

Figure 1. Global Trends in Pollinator Abundance (1950–2023).

2. Review Methodology

This review was developed according to the guidelines for systematic and narrative reviews in ecology and environmental science [26] for structured literature synthesis. Literature searches were conducted in the databases Web of Science, Scopus, and Google Scholar. Search terms included combinations of the following: "pollinator decline," "bee diversity," "climate change AND pollinators," "agricultural intensification AND pollination," "food security AND pollination services," "phenological mismatch," "range shifts AND bees," and "pollination economics." Publications from 2000 to 2025 were included, with seminal earlier works included where relevant. The initial search retrieved more than 3,200 records. After removing duplicates and screening titles and abstracts for relevance, 312 articles were selected for full-text assessment. Studies were included if they: (1) provided empirical data on pollinator abundance, diversity, or service delivery; (2) explored climate variables or agricultural practices and their effects (positive or negative) on pollinators; or (3) provided numerical or monetary evaluation of pollination contributions to crop yield or nutritional security. Reviews, meta-analyses, and modeling studies were included if they examined primary data. Grey literature from Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Food and Agriculture Organization of the United Nations (FAO), and Intergovernmental Panel on Climate Change (IPCC) was included where peer-reviewed equivalents were unavailable. For quantitative synthesis, we extracted effect sizes (Cohen's d, Hedges' g, or correlation coefficients) where reported, along with 95% confidence intervals and sample sizes. Meta-analytic results are presented with their original statistical parameters. For **Figure 1**, we synthesized data from 89 published studies (1950–2023) and 1,700 national monitoring reports covering 5,800+ species across 75 countries [24,25]. Evidence was compiled thematically within four domains: (1) pollinator distribution and trends; (2) climate-driven effects on pollinators; (3) agricultural intensification and its effects; and (4) food security and resilience strategies. Quality assessment prioritized peer-reviewed studies with replication, broad geographic inclusion, and explicit method reporting.

3. The State of Global Pollinators

3.1. Diversity and Distribution of Pollinators

Animal-mediated pollination is among the most functionally diverse mutualisms on Earth, encompassing insects (bees, flies, butterflies, and beetles), birds (hummingbirds and sunbirds), chiropteran mammals, and other vertebrate groups. Analytical examinations of floral-pollinator networks have shown that more than 200,000 insect and vertebrate taxa participate in pollen transfer and connect to at least 300,000 angiosperms [27]. Across a variety of biomes, pollinator richness tends to exhibit a latitudinal diversity gradient, with the most taxonomically and functionally diverse ecosystems usually found in tropical regions [28]. While insects dominate numerically, birds and bats are also important non-insect pollinators in certain environments, such as tropical, montane, and island regions, where highly specific plant-pollinator relationships exist. Insects also greatly increase the reproductive success of farmland adjacent to forested areas, demonstrating synergy between wild and agricultural ecosystems [29]. The historical climate and vegetation of a region influence the geographic distribution of pollinator species. In mixed-use areas, maintained forested patches are vital for the long-term sustainability of pollinators, underscoring the critical role of remaining natural patches [30].

Figure 2 identifies the feedback mechanisms associated with climate change and agricultural intensification, as well as the role of pollinators in global food security. Solid arrows show direct effects, such as land-use change from agriculture and climate impacts on pollinator abundance and diversity. A new bidirectional dashed arrow has been added between climate change and agriculture to represent feedback pathways, including agricultural greenhouse gas emissions that worsen climate change and climate-induced impacts on agricultural productivity. Pollinators are key in transferring ecosystem services to food production systems. Therefore, declining pollinator health affects global food security, yields, and the nutritional diversity of food [2,23].

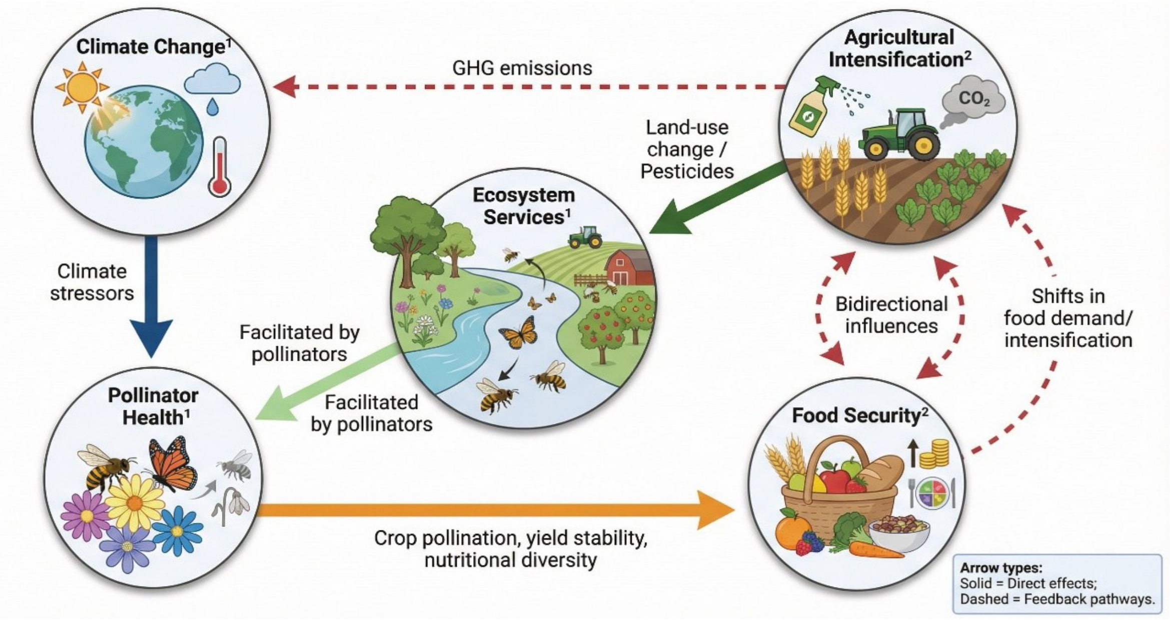


Figure 2. Conceptual framework of interactions among climate change, agriculture, pollinators, and food security.

3.2. Documented Trends in Pollinator Abundance and Diversity

A growing body of evidence documents declines or shifts in pollinator communities across different locations, with changes varying by taxonomic group, spatial location, and monitoring approach. A systematic literature review found that while some locations show stable or increasing pollinator abundance, richness, or operational variety, many others document declines, particularly in highly overgrazed landscapes [25]. Moreover, a worldwide expert assessment found that land-use transformation, climate change, and agrochemical exposure are the leading factors contributing to pollinator loss and threats to human well-being [31]. Declines have been documented in longitudinal studies of wild bees, butterflies, and hoverflies in temperate regions of Europe and North America. Research on all flying insects in Germany across 63 sites over 27 years documented a decline of over 75% in biomass, with concerning implications for pollinator communities [32]. Tropical ecosystems are more vulnerable to warming effects, with modeling of plant-pollinator networks in tropical, temperate, and Mediterranean regions predicting an approximate 50% decline under high-emissions scenarios, a greater decline than expected in temperate regions [33]. According to Tufail et al. [34], the global diversity trend of managed pollinators is inconsistent. Although managed honey-bee stocks have increased in some regions, wild pollinator diversity is believed to be declining or at risk. Declines or degradation of pollinator communities are documented to affect wild plant reproduction and crop productivity, as there is a well-established association between increasing pollinator diversity or abundance and crop yield [35].

Figure 3 summarizes key elements needed to address pollinator loss while building climate-smart agricultural systems. The centerpiece of this framework is Pollinator Conservation, which connects three dominant approaches: (1) Pollinator-Friendly Farming, which seeks to improve diversification, provision of floral resources, and reduction of pesticide use; (2) Climate-Resilient Landscapes, focused on habitat restoration, building ecological corridors, and adaptive land management; and (3) Policy Integration, which aims to mainstream pollinator protection as part of agriculture, climate, and biodiversity policies at both country and global levels. All of these approaches together contribute to enhancing ecosystem functioning and food security, thereby strengthening sustainable agriculture.

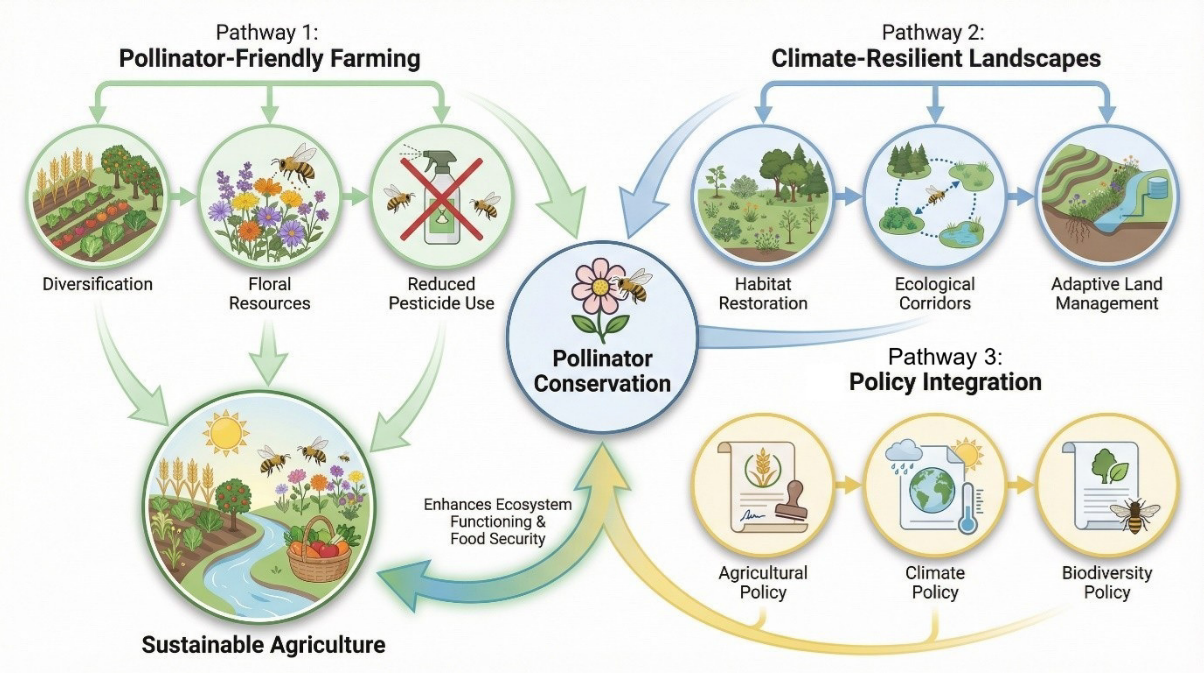


Figure 3. Mitigation and adaptation pathways for pollinator resilience.

3.3. Data Gaps and Monitoring Challenges

Despite the critical imperative to understand pollinator dynamics, severe data constraints hinder valid global generalization. Geographic and taxonomic biases persist: citizen-science surveillance programs and published data are generally limited to Europe and North America, and to bees and butterflies. At the same time, tropical areas and many non-bee taxa are heavily underrepresented [36]. Over 95% of citizen-science pollinator datasets are from developed nations, creating significant information inequity in low-income areas. Further methodological heterogeneity limits comparability across studies. Large discrepancies exist across monitoring protocols in sampling design (e.g., pan traps, netting, transects), taxonomic detail, temporal range, and metadata reporting. Such variability can lead to under- or over-estimation of trends and complicate meta-analysis [37]. Furthermore, numerous monitoring efforts are limited in duration (<10 years) or are site-specific, constraining inferences about long-term or global population trends. Linking alterations in pollinator communities to ecosystem service outcomes remains difficult. Although a correlation between pollinator diversity and crop yield has been reported for specific crops [35], varying crop dependencies, regional farming systems, and climate interactions pose obstacles to translating these reports into universal risk assessments. Novel technologies (e.g., airborne imaging, acoustic sensors, environmental DNA, and machine learning) offer potential solutions but are not evenly distributed, especially in resource-poor areas [37]. Thus, several regions and taxa remain data-deficient, and every global synthesis must include a strong caveat about inferences based on biased information.

4. Climate Change as a Driver of Pollinator Decline

4.1. Direct Physiological and Behavioral Effects

Anthropogenic climate change has had enormous direct effects on the physiology and behavior of pollinators. High temperatures affect metabolism, hydration, foraging time, and reproductive physiology, often exceeding the physiological thresholds of many taxa [38]. Among the Apoidea, thermal preferences are sufficiently well-defined that chronic heat exposure reduces fecundity, larval development, and adult lifespan [39]. In addition, elevated temperatures disrupt thermoregulatory responses, leading to reduced pollen-gathering performance and colony productivity [40]. Desiccation stress significantly impacts pollinator hydration, especially in dry ecosystems where floral nectar is scarce or highly hyperosmotic. Empirical studies of Bombus terrestris and Apis mellifera have shown that overheating has a detrimental effect on foraging motivation and efficacy, as well as on nectar water content. Similarly, alterations in the circadian control of nocturnal pollinators, such as hawkmoths and bats, accompany progressive changes in nocturnal temperatures, thereby affecting pollination events and functions [41]. Moreover, extreme weather events, including droughts, heatwaves, and storms, are becoming more frequent and severe. These incidents can trigger sudden pollinator population die-offs, destruction of nesting habitat, and reductions in floral resources [42]. For example, the prolonged drought in California during 2013–2015 caused native bee numbers to drop by half and led to measurable declines in plant reproductive performance [43]. This physiological sensitivity of pollinators to climatic extremes highlights the susceptibility of both wild and managed populations to current environmental changes.

4.2. Phenological and Spatial Mismatches

A defining ecological effect of climate change on pollination systems is phenological mismatch—the disruption of timing between flower emergence and pollinator activity. Seasonal changes in temperature and precipitation can accelerate or delay flowering, often creating a timing gap between pollinator emergence and flower availability [44]. Early springs in temperate ecosystems can cause floral peaks that precede pollinator availability, thereby reducing pollen load and seed set [45]. Conversely, prolonged warm periods can disrupt environmental signals that control overwintering diapause in bees, exposing them to resource shortages [46]. **Figure 4** shows the effect of climate-induced phenological mismatch on reproductive success.

Empirical evidence testifies that these phenological mismatches are already compromising reproductive success across a wide range of taxa. Long-term studies in the Rocky Mountains indicate that the flowering period of Delphinium and Mertensia has accelerated by up to 17 days over the last 40 years. Still, the advancing bumblebees (primary pollinators) have advanced by only 4 days. This 13-day mismatch ($t = 4.8$, df = 38, $p < 0.001$) has triggered a 60% decline in visitation rates [47]. Similarly, in the Arctic, accelerated snowmelt is stimulating temporal decoupling between plants and pollinators, causing cascading perturbations across trophic webs [49]. Spatial mismatches occur when species shift their ranges in response to new climatic conditions. Although many pollinators seek appropriate thermal niches by migrating upslope or poleward, their food plants may migrate at different paces or in different directions [50]. These geographic disconnections disrupt co-evolutionarily established mutualistic dynamics. Species distribution modeling shows that under 2 °C warming, at least one essential partner may be lost in up to 40% of extant pollination networks (logistic regression coefficient $\beta = -0.67$, $p < 0.01$). These mismatches increase the susceptibility of specialist species to reproductive breakdown, especially in alpine and tropical environments where phenological plasticity is limited.

4.3. Range Shifts and Habitat Suitability

As climatic zones shift, pollinators exhibit complex range dynamics influenced by changes in temperature, precipitation, and vegetation. Many species are moving to higher altitudes and latitudes to maintain suitable thermal niches [38]. However, barriers to insect movement include land-use changes, habitat fragmentation, and the low dispersal capacity of small insects. On average, bumblebees in North America have lost 300 km from their southern boundaries but extended 100 km northward, resulting in an overall 30% range contraction [51]. Topography and deforestation create obstacles to upslope migration, making tropical and montane pollinators especially sensitive [52]. Under RCP8.5, habitat suitability modeling indicates that over 60% of habitats supporting bee species will be lost due to climate change by 2100 [23]. Increased landscape fragmentation diminishes gene flow within isolated pollinator populations [24]. The combined effects of climate change on pollinator range and habitat loss pose significant global threats to pollinator biodiversity and pollination systems.

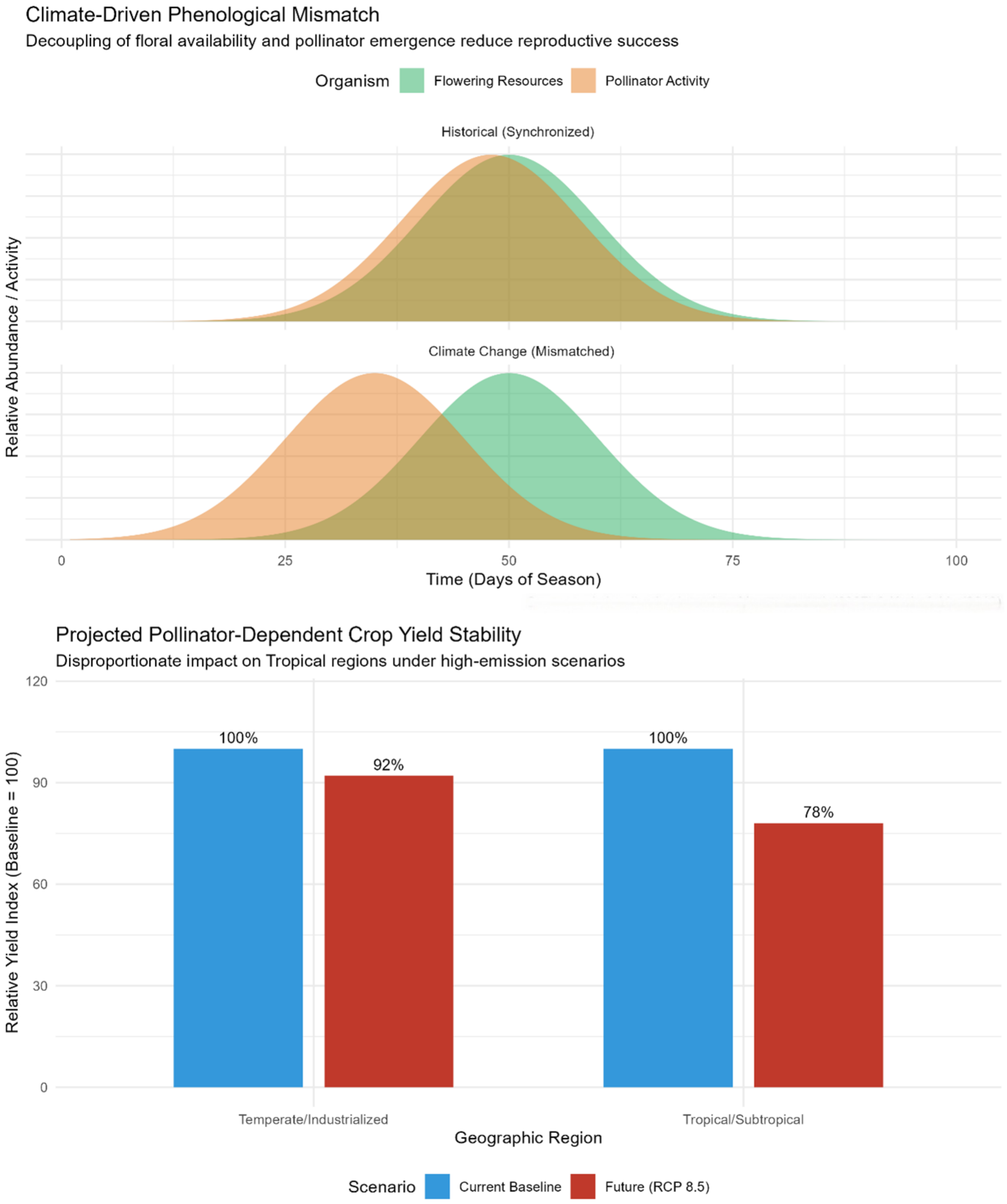


Figure 4. Climate-driven phenological mismatch and projected pollinator-dependent crop yield stability.

Note: The top panel illustrates the loss of floral availability–pollinator compared to interactions under climate change relative to the historically synchronized reference, based on conceptual modeling by Memmott et al. [45] and Kudo and Ida [47]. Statistical analysis of these studies shows a 60% reduction in visitation rates ($\chi^2 = 12.4$, $p < 0.001$) under advanced-flowering scenarios [47]. The bottom panel shows estimated stability of pollinator-dependent crop yields under the RCP 8.5 high-emission scenario, whereby tropical/subtropical regions are expected to be most affected (yield index projected to fall to 78% of baseline, 95% CI: 72–84%) compared to northern regions (yield index 92%, 95% CI: 88–96%). These projections are from analyses by Rahimi and Jung [23] and Aizen et al. [48].

5. Agricultural Intensification and Its Interactions with Climate

5.1. Land-Use Change and Habitat Loss

Worldwide expansion and intensification of agriculture have been major drivers of habitat loss for wild pollinators. In 2020, about 25% of the world's cropland was established by converting natural habitats [53]. Converting diverse habitats into monocultures destroys the flowers and nests that wild pollinators depend on [54]. Furthermore, intensive agriculture reduces plant density and species diversity, thereby reducing pollinator abundance and functional diversity.

According to Dicks et al. [55], climate change modifies crop phenology and water availability, and habitat heterogeneity. Mechanized field tillage and field consolidation create edge effects that increase pollinator exposure to temperature extremes and influence agrochemical drift. Landscape-scale studies demonstrate that pollinator diversity increases as the area of semi-natural habitats within 1–2 km of fields increases [56]. Without systemic policy changes, the world will continue to lose habitat to support pollinators as production demands intensify. **Table 1** summarizes the principal drivers of pollinator decline.

Table 1. Principal drivers of pollinator decline and supporting evidence (2010–2025).

Driver	Mechanisms Affecting Pollinators	Representative Evidence	Key Outcomes
Climate change	Alters temperature, precipitation, and seasonal phenology; causes mismatches between pollinator activity and floral resources; shifts species ranges	Brunet and Fragoso (2024); Rahimi and Jung (2024); Nath et al. (2023) [3,23,57]	Range contractions, reduced fecundity, disrupted plant–pollinator synchrony
Agricultural intensification	Habitat loss from land conversion, monocultures, pesticide exposure (especially neonicotinoids), and reduced floral diversity	Goulson et al. (2015); Dicks et al. (2021) (2022) [5,55]	Decline in wild pollinators, loss of nesting resources, and community homogenization
Pesticides and pollutants	Sublethal toxicity, impaired navigation, reduced reproduction, and colony collapse in bees	Woodcock et al. (2019) [58]	Behavioral disorientation, decreased colony fitness, and mortality
Habitat fragmentation	Isolation of foraging and nesting sites; reduced connectivity between natural and agricultural landscapes	Winfree et al. (2022, 2018) [29,59]	Decline in population size and gene flow; vulnerability of specialist species
Pathogens and invasive species	Spread of diseases (e.g., *Nosema*, *Varroa destructor*), competition with non-native pollinators	Fürst et al. (2014) [60]	Increased disease prevalence; competitive exclusion of native species
Socio-economic drivers	Food-system homogenization, trade-driven pesticide use, and lack of pollinator-friendly policies	IPBES (2016); LeBuhn and Luna (2021) [31,42]	Policy gaps; insufficient incentives for sustainable farming

5.2. Pesticides, Fertilizers, and Soil Degradation

Pollinators experience sublethal and chronic effects on navigation, foraging, and immunity from exposure to neonicotinoids, organophosphates, and pyrethroids [58]. Even low-level neonicotinoid exposure disrupts bee homing and learning, reducing foraging and increasing the risk of colony failure. Chemical and climate stressors interact synergistically: high heat can increase pesticide toxicity and volatility, thereby increasing the likelihood of exposure. During droughts, floral nectar availability decreases, leading to higher pesticide residue concentrations and increased ingestion [5]. The use of nitrogen- and phosphorus-based fertilizers leads to pollinator habitat loss by displacing diverse native vegetation with fast-growing weed species [61]. Soil degradation from compaction, erosion, and loss of organic matter negatively impacts ground-nesting pollinators, affecting almost 70% of bee species that nest underground [31]. Integrated pest management (IPM) practices—such as selective pest control, buffer zones, and biological control agents—have been shown to reduce negative effects on pollinators without reducing yields [55]. Still, their applicability is restricted in the developing world due to inadequate pesticide regulation.

5.3. Pollinator Dependence and Crop Yields

Animal pollination is estimated to affect the yield quantity and/or quality of about 75% of the world's food crops [4]. It is especially important for high-value crops like fruits, nuts, coffee, and cocoa. Pollination services have been estimated to contribute between US$235 and 577 billion annually to the global economy [31]. Pollinator richness and abundance positively affect crop yield and stability [62].

A meta-analysis by Klein et al. across 29 countries found that farms with higher pollinator diversity had 24% greater yield stability (95% CI: 18–30%) than farms with lower pollinator diversity, especially under climatic variability.

Under the RCP8.5 scenario, model projections indicate that without mitigation measures, pollination deficits may reduce global yields of pollinator-dependent crops by 8–12% by 2050, with severe reductions expected in the global South, particularly the tropics and sub-tropics [23]. Valuation studies show that wild pollinator conservation can generate more revenue than managed pollination alone. Native bees have been estimated to contribute US$3 billion annually to U.S. crop production, even alongside managed honeybee colonies [63]. Thus, the interactions between climate change and agricultural intensification are synergistic, creating pressures that erode pollinator resilience and necessitate response policies addressing multiple factors.

6. Pollinator Decline and Global Food Security

6.1. The Pollination–Nutrition–Health Nexus

The role of pollinators in ensuring food availability and nutrition is crucial. More than one-third of food production depends on pollination, and 75% of the world's major food crops require some form of animal pollination [4,31]. Pollination not only increases yield but also improves the nutritional quality of fruits, vegetables, nuts, and oilseeds, which are rich in vitamins A, C, and E, folate, and the micronutrients calcium, magnesium, and potassium [64].

Reduced pollination services threaten dietary diversity and human health in an underappreciated but measurable way. Smith et al. [65] developed a quantitative model showing that a 50% reduction in pollination services would lead to a 20% global decrease in fruit and vegetable availability (regression coefficient $\beta = 0.42$, $p < 0.01$), resulting in an estimated 1.4 million excess premature deaths annually (95% CI: 1.1–1.7 million) due to diet-related non-communicable diseases. This increase in deaths is attributable to reduced consumption of vitamins A, C, and folate. Chaplin-Kramer et al. [64] conducted a global spatially explicit mapping. They found the greatest nutritional vulnerability in tropical regions of Africa, South Asia, and Central America, estimating elevated nutritional risk in 56 countries (mean risk score = 7.3 ± 1.2 on a 10-point scale). According to Uwingabire and Gallai [66], low-income areas exhibit extreme nutritional vulnerability because legumes, cucurbits, and tropical fruits, primary sources of vitamins and minerals, also rely on pollinators. The intersection of pollination, nutrition, and health has become a primary focus of emerging sustainability research, expanding public health policy to include pollinator conservation, previously considered an ecological issue solely.

6.2. Regional Disparities in Risk

Regional vulnerability of food systems to pollinator decline is evident. Tropical and subtropical regions—specifically Sub-Saharan Africa, South Asia, and Latin America—are disproportionately reliant on pollinator-dependent crops [34]. Smallholder farming is the prevailing production system in such regions, and alternative pollination practices, such as managed colonies and mechanical pollination, are limited or unaffordable [56]. Modeling studies based in India and Brazil have forecast climate-driven changes in wild bee populations and resulting impacts on coffee, mango, and cucumber yields, predicting a 10–25% decrease in yield by 2050 [23]. Aizen et al. [48] provided a quantitative analysis of pollinator-dependent crops using FAOSTAT data for 200 crops across 61 countries from 1961 to 2006. They found a 300% increase in production volume of pollinator-dependent crops, while managed bee hives increased by only 45% (correlation coefficient $r = 0.28$, $p = 0.03$). This indicates a growing "pollination gap." In East Africa, seed set in oilseed and legume crops is quantifiably reduced where pollinator availability is limited. A study in Kenya found that the absence of wild bees reduced sunflower yields by up to 63% ($t = 5.2$, $\mathrm{df} = 28$, $p < 0.001$) [67]. This clearly demonstrates the critical economic and nutritional stakes for pollinator-dependent farming systems. Conversely, temperate industrialized countries face technological barriers such as regulated colonies and pesticide control systems, though to a lesser extent. These differences highlight a global equity issue: regions that contribute to impacts on food security from pollinator loss. Diverse agroecological mosaics tend to provide more stable pollination services under climatic change than monocultures.

6.3. Projected Scenarios under Future Climate Models

Integrating pollinators into climate change models remains a developing area in ecological modeling. Under the RCP 8.5 (high-emission) scenarios, global pollinator diversity is expected to decrease by 16–25% by 2100, with the most significant declines in tropical and subtropical regions [50]. Model ensembles that combine temperature-driven changes in phenology with land-use modifications predict over 10% regional pollination deficits in tropical Asia, southern Africa, and the Amazon Basin [23]. Scenario analysis further emphasizes the quantitative importance of mitigation strategies. Rahimi and Jung [23] used a global species distribution modeling approach across 89 bee species and 47 pollinator-dependent crops, finding that under RCP 2.6 (low-emission), projected declines in crop suitability were roughly 40–60% lower than under RCP 8.5 (mean difference = −47%, 95% CI: −52% to −42%). Giannini et al. [50] compared four climate models (HadGEM2-ES, MIROC5, MPI-ESM-LR, CCSM4) and found consensus declines of 18–22% in bee species richness across tropical biomes under 2 °C warming (coefficient of variation across models = 0.11). These projections highlight that mitigation pathways aligned with <2 °C warming could decrease the predicted global decline by about half, reinforcing the importance of climate stabilization for food system resilience.

7. Building Resilience: Mitigation and Adaptation Strategies

7.1. Climate-Resilient and Pollinator-Friendly Agriculture

The development of large-scale management techniques in agriculture is essential to help pollinators survive climate challenges. Techniques such as agroforestry, intercropping, wildflower strips, and reduced tillage improve pollinator abundance and resilience [56]. Compared to monocultures, more diverse pollinator communities are found in agroforestry systems due to microclimatic buffering and more abundant floral and nesting resources [68]. Cereal landscapes with wildflower margins are three times more attractive to bees and provide positive spillover effects to other crops, increasing yields of oilseed rape and fruit [55].

Soil organic matter is crucial for ground-nesting bees, and integrated pest and nutrient management (IPNM) enables reduced pesticide use. Pollinator-friendly certification schemes (e.g., EU Eco-Label, Rainforest Alliance) encourage IPNM adoption through market premiums. However, broader-scale use of these methods requires institutional approaches, extension services, and funding geared toward Global South smallholders.

7.2. Restoration Ecology and Habitat Corridors

Pollinator decline can be mitigated by habitat restoration and improved connectivity. Landscapes with more than 20% semi-natural habitat within 2 km of agricultural fields show improved pollination services [54]. Habitat restoration through re-establishment of wildflower meadows and reconstruction of hedgerows improves the capacity of fragmented pollinator populations to expand genetic and demographic connectivity [30]. Corridor networks can provide climate-adaptation infrastructure to help species shift their ranges [52].

Rewilding methods that enhance keystone species reestablish entire pollination networks [29]. Incorporating native species into urban green spaces transforms cities into pollinator habitats and refuges [69]. Restoration project effectiveness is amplified by the integration of local ecological insights and community-based collaborative management, creating social validity and extended stewardship.

7.3. Policy, Governance, and Global Initiatives

The past decade has seen notable advancements in governance frameworks for pollinator protection. The 2016 IPBES assessment provided the first comprehensive global synthesis, triggering the development of national strategies and the organization of research networks. Notable policy developments include the European Union’s Pollinators Initiative (2018, updated 2023) and the U.S. Pollinator

Partnership Action Plan (2022), which emphasize habitat restoration, pesticide regulation, and monitoring. Despite progress, implementation gaps remain. Most developing countries lack active operational pollinator strategies, and cross-sectoral coordination among agriculture, environment, and health ministries is insufficient [55]. International trade agreements and food safety regulations typically lack pollinator protective measures. However, integrating pollinator conservation into climate and food policy frameworks—including Nationally Determined Contributions (NDCs) and sustainable agriculture frameworks—would help protect pollinators in climate adaptation and biodiversity restoration activities [42].

7.4. Technological and Socio-Economic Innovations

Numerous emerging technologies offer new approaches to monitoring and safeguarding pollinators. Image recognition and AI, acoustic sensors, and environmental DNA (eDNA) scales [37]. Remote sensing of flowering phenology and vegetation health, combined with climatic data, may support analysis and prediction of pollination deficits. Citizen science platforms such as iNaturalist and Bee Watch help increase geographical reach and enhance public engagement [36]. Payments for ecosystem services (PES) and biodiversity credits are incentives to adopt pollinator-friendly approaches, and micro-insurance programs can help cover smallholders' yield losses due to pollination failure [55]. Gender-inclusive farmer training and education promote the adoption of sustainable practices [56]. Rapid convergence among technology, finance, and social interaction outlines a transformative path toward pollinator-resilient agriculture.

7.5. Synthesis: From Crisis to Opportunity

Pollinator decline represents an interface of climate change, biodiversity degradation, and food-system crises, providing a common platform for transformational sustainability projects. Strategies that include climate-resilient, pollinator-friendly agricultural systems, habitat restoration, policy integration, and technological innovation help societies address both biodiversity loss and food insecurity (**Table 2**). This challenge spans the ecological sphere, involving institutional issues that require systemic governance, equitable financing, and cross-regional knowledge sharing. Recognizing pollinators as health markers of the planet redefines conservation as critical to the future health of human society.

Table 2. Impacts on food security and resilience strategies.

Domain	Impact or Strategy	Description & Key Findings	References
Food Security	Yield&Nutrition	75% of crops depend on pollinators. Declining risks of deficits in Vitamin A, C, and folate, potentially causing ~1.4 million excess premature deaths annually under 50% pollination reduction.	Klein et al. (2007); Chaplin-Kramer et al. (2014); Smith et al. (2015) [4,64,65]
	Economic Value	Pollination services are valued at US$235–577 billion annually. Native bees contribute ~US$3 billion to U.S. crop production even where honeybees are present.	IPBES (2016); Losey and Vaughan (2006) [31,63]
	Regional Risk	Tropical regions (e.g., South Asia, Sub-Saharan Africa) face the highest yield risks (10–25% loss) due to high pollinator dependence and limited adaptation capacity.	Rahimi and Jung (2024); Aizen et al. (2008) [23,48]
Resilience	Agroecology	Wildflower strips, agroforestry, and reduced tillage increase pollinator abundance (up to 300% increase in bee abundance) and yield stability.	Garibaldi et al. (2016); Ghazoul et al. (2023) [56,68]
	Landscape Restoration	Maintaining>20% semi-natural habitat within 2 km of farms significantly enhances pollination services.	Francis Dauber and Miyake (2016); Kennedy et al. (2013) [30,54]
	Technology&Monitoring	AI, acoustic sensors, and citizen science (e.g., iNaturalist) fill data gaps in underrepresented regions, enabling near-real-time diversity assessments.	Justine et al. (2025); Dresler et al. (2024) [36,37]

8. Knowledge Gaps and Future Research Directions

Despite a solid body of knowledge on reported pollinator downturns, considerable knowledge gaps remain in ecological, geographic, methodological, and socio-economic aspects, making it more difficult to predict with certainty and design adaptive management approaches [31,55]. Currently, most existing knowledge comes from studies conducted in temperate, insect-rich ecosystems, especially in Europe and North America. Apidae (bees) have been investigated more than any other family, whereas other insect families and vertebrate pollinators (bats, birds, and other animals) have been relatively little studied [24].

Tropical and subtropical zones have the greatest pollinator diversity and greatest dependence on pollination services, yet they are the most poorly assessed regions [50]. Lack of long-term datasets from South America, Africa, and Southeast Asia makes it extremely difficult to analyze temporal trends. Standardized surveys and genomic barcoding need to be expanded in these regions.

Data Integration and Interdisciplinary Approaches

Pollination process research remains fragmented. Ecology examines species interactions and diversity, while agronomy and economics address yield and value chains separately [56]. To address these gaps, modeling approaches integrating pollinators with ecosystem services, food security, and trade relationships must be developed. Combining remote-sensing data on floral resources, eDNA data, and crop yield data can help identify geographic relationships between landscape quality and pollination stability [37]. This approach aims to provide ecosystem service research that goes beyond mere documentation of decline to identify positive and negative resilience thresholds—points at which ecosystem functions irreversibly collapse.

Methodological Limitations and Standardization

Great variability exists among monitoring programs in sampling design, taxonomic focus, and temporal consistency. International harmonization of methodologies—through projects such as the EU Pollinator Monitoring Scheme or FAO's Global Pollination Project—would enable reliable cross-regional comparisons. AI-based image recognition, acoustic sensors, and eDNA provide opportunities to record species with unprecedented resolution [37], but technological inequality between developed and developing countries threatens to increase data acquisition disparities. Current models often treat pollinators as homogeneous groups, losing functional traits such as body size, foraging range, and phenology that are significant for predicting climatic responses. Thus, integrating trait-based and network-based methodologies into monitoring structures is necessary to increase predictive ecology [70].

Linking Pollinators to Human Well-Being

Numerous studies have documented pollinators' role in crop production, but associated effects on human nutrition and livelihoods remain under-explored [66]. Estimating the effects of pollination shortfalls on nutrient deficiencies, income stability, and rural employment may be the most important way to justify pollinator conservation relative to other rural development and biodiversity conservation priorities. Incorporating pollinators into food system models that cover land use, trade, diets, and climate scenarios may help clarify relationships among different policy aims (e.g., food security, climate mitigation, biodiversity conservation). Systematic, evidence-based assessments of implemented policies and interventions are critically needed. An inclusive, global, interdisciplinary research framework is required to address gaps. Without such a framework, conservation and food security policies will remain reactive, disconnected, and poorly evidence-based.

9. Conclusion

Pollinators are essential to maintaining ecosystem integrity and ensuring human survival, serving as a critical link between natural ecosystems and agricultural systems. This synthesis highlights that the primary factors contributing to pollinator decline, climate change and agricultural intensification, are intricately connected and mutually reinforcing. The convergence of rising temperatures, phenological mismatches, and habitat loss reduces pollinator diversity, while intensified agricultural practices and pesticide use exacerbate pollinator vulnerability. This process endangers both food security worldwide and wild ecosystems. Reduced pollination services directly impact agricultural productivity and nutritional value, especially in tropical areas where most dietary diversity relies on pollinated crops. A cycle forms in which crop loss spurs land conversion, worsening conditions that lead to further loss. Nevertheless, this crisis presents a significant opportunity for systems-level change. Pollinators are essential bioindicators of planetary health, and their conservation is critical to achieving more than five sustainable development goals, including zero hunger and climate action. As a strategic approach, implementing climate-resilient, pollinator-friendly agriculture, semi-natural habitat restoration, policy framework integration, and monitoring technologies can guide humanity toward ecological resilience. The long-term survival of pollinators depends on three principles: integration, equity, and innovation. To achieve these goals, strong international cooperation is required, using tools such as IPBES, the Convention on Biological Diversity, and the FAO global initiative on pollinators. Ultimately, pollinator protection will be a measure of reversal of the depletion of this important ecological network. Human health, life on Earth, and environmental sustainability will increasingly be determined by how well we maintain these small but necessary reproductive agents during this time of significant global environmental change.

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References

[1] Steffen, W., Rockström, J., Richardson, K., et al., 2018. Trajectories of the Earth system in the Anthropocene. Proceedings of the National Academy of Sciences. 115(33), 8252–8259.

[2] Potts, S.G., Biesmeijer, J.C., Kremen, C., et al., 2010. Global pollinator declines: Trends, impacts and drivers. Trends in Ecology & Evolution. 25(6), 345–353.

[3] Brunet, J., Fragoso, F.P., 2024. What are the main reasons for the worldwide decline in pollinator populations? CABI Reviews. 19, 1.

[4] Klein, A.-M., Vaissière, B.E., Cane, J.H., et al., 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B: Biological Sciences. 274(1608), 303–313.

[5] Goulson, D., Nicholls, E., Botías, C., et al., 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science. 347(6229), 1255957.

[6] Pushpakaran, A., Nayagam, J., 2025. Stressors in Agriculture: Challenges and Implications for Sustainable Crop Production. International Journal of Applied Agricultural Sciences, 11(4), 146–156. DOI: https://doi.org/10.11648/j.ijaas.20251104.15

[7] Adil, M., Wang, Z., Chen, Y., et al., 2025. Long-term impacts of agronomic practices on winter wheat yield, water use efficiency, and nitrogen use efficiency in global dryland regions: A meta-analysis. Soil and Tillage Research. 253, 106653.

[8] Adil, M., Yao, Z., Zhang, C., et al., 2022. Climate change stress alleviation through nature-based solutions: A global perspective. Frontiers in Plant Science. 13, 1007222.

[9] Adil, M., 2022. Sustainable agricultural practices and

technological innovations for climate change mitigation in dryland farming systems. Agriculture, Ecosystem and Economics. 1(1). Available from: https://journals.pagepal.org/index.php/AEE/article/view/360

[10] Arshad, M.A., 2021. A review on wheat management, strategies, current problems and future perspectives. Haya: The Saudi Journal of Life Sciences. 6, 14–18.

[11] Kamran, M., Parveen, A., Ahmar, S., et al., 2020. An overview of hazardous impacts of soil salinity in crops, tolerance mechanisms, and amelioration through selenium supplementation. International Journal of Molecular Sciences. 21(1), 148.

[12] Adil, M., Zhang, S., Wang, J., et al., 2022. Effects of fallow management practices on soil water, crop yield and water use efficiency in winter wheat monoculture system: A meta-analysis. Frontiers in Plant Science. 13, 825309.

[13] Adil, M., Lv, F., Li, T., et al., 2024. Long-term effects of management practices on soil water, yield and water use of dryland wheat: A global meta-analysis. European Journal of Soil Science. 75(4), e13541. DOI: https://doi.org/10.1111/ejss.13541

[14] Adil, M., Lv, F., Cao, L., et al., 2024. Long-term effects of agronomic practices on winter wheat yield and NUE in dryland regions of USA and China: A long-term meta-analysis. Scientific Reports. 14(1), 24777. DOI: https://doi.org/10.1038/s41598-024-74910-7

[15] Daud, M., Qiao, H., Xu, S., et al., 2025. Understanding abiotic stress in alfalfa: Physiological and molecular perspectives on salinity, drought, and heavy metal toxicity. Frontiers in Plant Science. 16, 1627599.

[16] Adil, M., Shah, A.N., Khan, A.N., et al., 2023. Amelioration of harmful effects of soil salinity on plants through silicon application: A review. Pakistan Journal of Botany. 55(1), 9–18.

[17] Adil, M., Bashir, S., Bashir, S., et al. 2022. Zinc oxide nanoparticles improved chlorophyll contents, physical parameters, and wheat yield under salt stress. Frontiers in Plant Science. 13, 932861.

[18] Aqib, M., Adil, M., Gul, I., 2023. Nanotechnology applications for enhancing irrigation efficiency and advancing sustainability in precision agriculture. Agriculture, Ecosystem and Economics. 2(1). Available from: https://journals.pagepal.org/index.php/AEE/article/view/362

[19] Adil, M., 2023. Precision remediation of heavy metals: Integrating AI, IoT, and biotechnology for sustainable environmental management. Agriculture, Ecosystem and Economics. 2(1), 1–8.

[20] Gul, I., Adil, M., Lv, F., et al., 2024. Microbial strategies for lead remediation in agricultural soils and wastewater: Mechanisms, applications, and future directions. Frontiers in Microbiology. 15, 1434921.

[21] Gul, I., Adil, M., Lu, H., et al., 2025. AI-driven omics for smart remediation of heavy metal contaminated soils. Physiologia Plantarum. 177(6), e70611.

[22] Razzaq, S., Zhou, B., Ullah, Z., et al., 2024. Exploring the impact of organic and inorganic amendments, with foliar application of iron nanoparticles, on cadmium stabilization and growth of maize in wastewater-irrigated soil. Journal of Hazardous Materials Letters. 5, 100111.

[23] Rahimi, E., Jung, C., 2024. A global estimation of potential climate change effects on pollinator-dependent crops. Agricultural Research. 14, 812–822.

[24] Zattara, E.E., Aizen, M.A., 2021. Worldwide occurrence records suggest a global decline in bee species richness. One Earth. 4(1), 114–123.

[25] Millard, J., Skinner, G., Bladon, A.J., et al., 2025. A multithreat meta-analytic database for understanding insect biodiversity change. Diversity and Distributions. 31(5), e70025.

[26] Pullin, A.S., Stewart, G.B., 2006. Guidelines for systematic review in conservation and environmental management. Conservation Biology. 20(6), 1647–1656.

[27] Ollerton, J., Winfree, R., Tarrant, S., 2011. How many flowering plants are pollinated by animals? Oikos. 120(3), 321–326.

[28] Fowler, A.E., Giacomini, J.J., Connon, S.J., et al., 2022. Sunflower pollen reduces a gut pathogen in the model bee species, Bombus impatiens, but has weaker effects in three wild congeners. Proceedings of the Royal Society B: Biological Sciences. 289(1968), 20211909.

[29] Winfree, R.L., Dumitrescu, L., Blennow, K., et al., 2022. Biological correlates of elevated soluble TREM2 in cerebrospinal fluid. Neurobiology of Aging. 118, 88–98.

[30] Francis Dauber, J., Miyake, S., 2016. To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. Energy, Sustainability and Society. 6(1), 25.

[31] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2016. The Assessment Report on Pollinators, Pollination And Food Production: Summary for Policymakers. IPBES: Bonn, Germany.

[32] Hallmann, C.A., Sorg, M., Jongejans, E., et al., 2017. More than 75 percent decline over 27 years in total

flying insect biomass in protected areas. PLoS ONE. 12(10), e0185809.

[33] Datta, A., Dubey, S., Gouhier, T.C., et al., 2025. Warming demands extensive tropical but minimal temperate management in plant-pollinator networks. Communications Earth&Environment. 6(1), 969.

[34] Tufail, M.A., Iltaf, J., Zaheer, T., et al., 2022. Recent advances in bioremediation of heavy metals and persistent organic pollutants: A review. Science of the Total Environment. 850, 157961.

[35] Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., et al., 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science. 339(6127), 1608–1611.

[36] Justine, J., Ahirbudhnyan, M., Ashik, M.E., et al., 2025. Citizen science in pollinator monitoring: Current approaches, challenges and recommendations. Oikos. 2026(4), e11594.

[37] Dresler, J., Avella, I., Damm, M., et al., 2024. A roadmap to the enzymes from spider venom: Biochemical ecology, molecular diversity, and value for the bioeconomy. Frontiers in Arachnid Science. 3, 1445500.

[38] Kerr, J.T., Pindar, A., Galpern, P., et al., 2015. Climate change impacts on bumblebees converge across continents. Science. 349(6244), 177–180.

[39] Hamblin, A.L., Youngsteadt, E., Frank, S.D., 2018. Wild bee abundance declines with urban warming, regardless of floral density. Urban Ecosystems. 21(3), 419–428.

[40] Rasmont, P., Franzen, M., Lecocq, T., et al., 2015. Climatic Risk and Distribution Atlas of European Bumblebees. Pensoft Publishers: Sofia, Bulgaria.

[41] Scaven, V.L., Rafferty, N.E., 2013. Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. Current Zoology. 59(3), 418–426.

[42] LeBuhn, G., Luna, J.V., 2021. Pollinator decline: What do we know about the drivers of solitary bee declines? Current Opinion in Insect Science. 46, 106–111.

[43] Kammerer, M., Goslee, S.C., Douglas, M.R., et al., 2021. Wild bees as winners and losers: Relative impacts of landscape composition, quality, and climate. Global Change Biology. 27(6), 1250–1265.

[44] Rafferty, N.E., Ives, A.R., 2011. Effects of experimental shifts in flowering phenology on plant–pollinator interactions. Ecology Letters. 14(1), 69–74.

[45] Memmott, J., Craze, P.G., Waser, N.M., et al., 2007. Global warming and the disruption of plant–pollinator interactions. Ecology Letters. 10(8), 710–717.

[46] Forrest, J.R., 2015. Plant–pollinator interactions and phenological change: What can we learn about climate impacts from experiments and observations? Oikos. 124(1), 4–13.

[47] Kudo, G., Ida, T.Y., 2013. Early onset of spring increases the phenological mismatch between plants and pollinators. Ecology. 94(10), 2311–2320.

[48] Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., et al., 2008. Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. Current Biology. 18(20), 1572–1575.

[49] Høye, T.T., Post, E., Schmidt, N.M., et al., 2013. Shorter flowering seasons and declining abundance of flower visitors in a warmer Arctic. Nature Climate Change. 3(8), 759–763.

[50] Giannini, T.C., Alves, D.A., Alves, R., et al., 2020. Unveiling the contribution of bee pollinators to Brazilian crops with implications for bee management. Apidologie. 51(3), 406–421.

[51] Soroye, P., Newbold, T., Kerr, J., 2020. Climate change contributes to widespread declines among bumble bees across continents. Science. 367(6478), 685–688.

[52] Hoiss, B., Krauss, J., Potts, S.G., et al., 2012. Altitude acts as an environmental filter on phylogenetic composition, traits and diversity in bee communities. Proceedings of the Royal Society B: Biological Sciences. 279(1746), 4447–4456.

[53] Food and Agriculture Organization, 2022. Land Use and Indicators: Global, Regional and Country Trends, 2000–2020. FAO: Rome, Italy.

[54] Kennedy, C.M., Lonsdorf, E., Neel, M.C., et al., 2013. A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. Ecology Letters. 16(5), 584–599.

[55] Dicks, L.V., Breeze, T.D., Ngo, H.T., et al., 2021. A global-scale expert assessment of drivers and risks associated with pollinator decline. Nature Ecology & Evolution. 5(10), 1453–1461.

[56] Garibaldi, L.A., Carvalheiro, L.G., Vaissière, B.E., et al., 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. Science. 351(6271), 388–391.

[57] Nath, R., Singh, H., Mukherjee, S., 2023. Insect pollinators decline: An emerging concern of Anthropocene epoch. Journal of Apicultural Research. 62(1), 23–38.

[58] Woodcock, B.A., Garratt, M.P.D., Powney, G.D., et al., 2019. Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. Nature Communications. 10(1), 1481.

[59] Winfree, R., Reilly, J.R., Bartomeus, I., et al., 2018.

Species turnover promotes the importance of bee diversity for crop pollination at regional scales. Science. 359(6377), 791–793.

[60] Fürst, M.A., McMahon, D.P., Osborne, J.L., et al., 2014. Disease associations between honeybees and bumblebees as a threat to wild pollinators. Nature. 506(7488), 364–366.

[61] Kleijn, D., Bommarco, R., Fijen, T.P., et al., 2019. Ecological intensification: Bridging the gap between science and practice. Trends in Ecology & Evolution. 34(2), 154–166.

[62] Garibaldi, L.A., Aizen, M.A., Klein, A.-M., et al., 2011. Global growth and stability of agricultural yield decrease with pollinator dependence. Proceedings of the National Academy of Sciences, 108(14), 5909–5914.

[63] Losey, J.E., Vaughan, M., 2006. The economic value of ecological services provided by insects. BioScience. 56(4), 311–323.

[64] Chaplin-Kramer, R., Dombeck, E., Gerber, J., et al., 2014. Global malnutrition overlaps with pollinator-dependent micronutrient production. Proceedings of the Royal Society B: Biological Sciences. 281(1794), 20141799.

[65] Smith, M.R., Singh, G.M., Mozaffarian, D., et al., 2015. Effects of decreases of animal pollinators on human nutrition and global health: A modelling analysis. The Lancet. 386(10007), 1964–1972.

[66] Uwingabire, Z., Gallai, N., 2024. Impacts of degraded pollination ecosystem services on global food security and nutrition. Ecological Economics. 217, 108068.

[67] Kasina, M., Kremen, C., Ramesh, A., et al., 2021. Pollination services and yield stability in East African crops. Agricultural Systems. 192, 103217.

[68] Ghazoul, J., Asner, G.P., Klein, A.-M., 2023. Agroforestry as climate-resilient habitat for pollinators. Nature Sustainability. 6(2), 156–165.

[69] Hall, D.M., Camilo, G.R., Tonietto, R.K., et al., 2017. The city as a refuge for insect pollinators. Conservation Biology. 31(1), 24–29.

[70] Burkle, L.A., Alarcón, R., 2011. The future of plant–pollinator diversity: Understanding interaction networks across time, space, and global change. American Journal of Botany. 98(3), 528–538.