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Effects of Climatic Change on Honeybees - Review article

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Abstract: A review of the honeybee (*Apis mellifera*), one of the most significant pollinators for ecosystems and agriculture, is given in this review. It is regarded as a vital yet delicate contributor to global biodiversity and food security, alongside many other species that are facing previously unheard-of challenges due to uneven climate drivers. The impact of climate change on honeybee habitats is a concern for scientists. This review study examines the complex relationship between honeybee health and climate change, which may lead to behavioral changes. It also discusses how foraging, reproduction, and colony survival are impacted by variations in temperature and weather patterns. The various processes that demonstrate their vulnerability will be the focus of this study, which will also underscore the urgent need for comprehensive strategies to mitigate the potential outcomes of policy implementation.
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1. Introduction

Apis mellifera, or honeybees, are essential pollinators of many agricultural crops and natural plants. as a controlled species that beekeepers travel the world with(Calderone 2012). Healthy bee populations are essential to this massive contribution to food supply and terrestrial biodiversity. However, a number of environmental stressors, such as climate change, are putting honeybees under increasing strain(Alaux et al. 2010).

Climate change is a major danger to ecosystems and biodiversity across the planet. The pollinators of many crops and wild plants, honeybees (*Apis mellifera*), are most impacted by these changes. Climate change's effects on honeybee numbers, behavior, physiology, and wider ecological ramifications are examined in this paper. The consequences of climate change have just lately been apparent; therefore, before creating mitigation plans, it is critical to understand how this worldwide phenomenon impacts bee activity and its interactions with food plants. There is a lack of scientific study on the specific effects pollinators will have, especially on food plants, despite worries about the possible harmful consequences of climate change. The temperature sensitivity of agricultural plants and their pollinators is not well understood, especially in the tropics, where the variety of entomophilous crops is expected to be highest(Matangi Mishra et al. 2023).

These days, heat stress is becoming a major problem for honeybees in apiculture since it can have detrimental effects on the health of honeybees, the bee colony, and the financial viability of the business. By combining previous studies, this study seeks to give reliable information by doing a detailed analysis of the effects of heat stress on honeybee populations. The *Apis mellifera*-specific thermoregulation mechanism in honeybees and related behavioral and biochemical adaptations in worker bees addresses the different ways that individual bees react to heat stress, such as how their eating patterns and metabolic rate alter. The study also offers a thorough examination of the impacts of heat stress on the whole bee colony, including impaired brood development, lower production, and increased vulnerability to parasites and diseases. Additionally, it looks at how heat stress affects bee health in conjunction with other stressors such pesticide exposure, nutritional stress, biotic pressures, and habitat loss(Kamboj, Kaur, and Gupta 2024).

This study emphasizes the necessity of multidisciplinary research and the identification of health stress as a significant factor impacting honeybee populations to protect these crucial pollinators from the detrimental impacts of climate change.

1. Temperature Fluctuations and Honeybee Physiology.

The rise in global temperatures is one of the most obvious consequences of climate change. Since honeybees are ectothermic, the temperature outside affects both their body temperature and metabolic functions. Several physiological problems can be brought on by high temperatures:

Significant changes to terrestrial natural ecosystems and processes have been projected as a result of global warming. As a component of terrestrial ecosystems, forests aid in the control of biogeochemical functions and processes. One function that benefits the forest ecology and related agroecosystems is insect pollination. The behaviors, distribution, and abundance of insect pollinators that live in forests are believed to be significantly impacted by climate change. In general, higher temperatures may have an impact on the insect pollinators that are found in forests(Kataria and Edgaonkar 2023). Significant changes in insect behavior, pesticide sensitivity, and phenological synchronization with host plants might result from climate change(Amala, Kesavan, and Shivalingaswamy 2022).

1.1. Thermoregulation:

By impeding fertility, body thermoregulation, foraging activities, and other regular bodily processes, heat stress has an impact on honeybee development and growth. Heat stress's effects on honeybees provide serious obstacles to their general colony survival as well as their physiological behaviors and general wellbeing. Diseases and parasites travel more readily in warm weather. The challenges of reducing heat stress's impact on honeybee populations are highlighted by the intricate interactions it has with other stressors. A comprehensive strategy that includes both short-term management techniques and long-term climate change mitigation initiatives is needed to address this challenge. Researching and utilizing natural, bee-friendly substitutes for synthetic chemicals is crucial for controlling pesticides and insecticides, as their usage in agriculture can result in bee poisoning and death. Nectar, clean water, and pollen are essential for honeybees, thus pollution that affects the environment or the bees should be prevented or managed. As climate change causes global temperatures to rise(Kamboj, Kaur, and Gupta 2024).

Bees' metabolic rates are accelerated by higher temperatures, which shortens their foraging time. Because it raises their metabolic rates and reduces their essential foraging time, increased global heat brought on by climate change poses a danger to honeybees. Because they are ectothermic, honeybees' body temperatures reflect those of their surroundings(Hu et al. 2021). Temperature has a significant impact on honeybee behavior and output. The brood comb is kept at a temperature of 33 to 36°C and a relative humidity of around 70%. Temperature variations have a major impact on honeybee lifespan, although humidity levels between 30% and 75% do not. Eventually, honeybees will become less resilient to extremes in temperature(Petz, Stabentheiner, and Crailsheim 2004). For example, a previous study (Calovi et al. 2021), found that honeybee survival was considerably lowered by higher temperatures. Due of their sensitivity to temperature stress brought on by severe temperatures, foragers steer clear of gathering nectar and pollen in extremely hot or cold conditions(Bordier et al. 2018). Temperature increases raise metabolic rates, which increases the amount of food consumed. This may put a burden on the hive's resources, particularly if climate change also affects the supply of foo.(Woods, Heinrich, and Stevenson 2005)

The average hive temperature is kept at 35°C by honeybees. This control becomes more challenging in warmer weather, which might result in overheating and hive collapse(Stabentheiner and Kovac 2016). Bees' foraging time is limited by higher temperatures because they speed up their metabolic rates. Because rising global temperatures brought on by climate change accelerate metabolic rates and reduce crucial foraging time, honeybees are at serious risk. Because they are ectothermic, honeybees' internal body temperatures reflect those of their surroundings(Hu et al. 2021). Bees' metabolism, heart rate, and mobility are all accelerated by higher ambient temperatures, which causes their energy stores to be depleted more quickly(Chiappetta Jabbour et al. 2020). The amount of time bees may spend searching for pollen and nectar outside the hive before returning to rest and replenish is limited by this energy stress(Garczynski, Cattaneo, and Walker III 2019).

2. Altered Flowering Times and Food Availability.

Plant phenology is impacted by climate change, which changes when plants blossom. This may cause a discrepancy between the time of year when honeybee activity is at its highest and the availability of floral resources: Persistent endothermy throughout the foraging cycle allows honeybees to quickly and efficiently exploit nectar and pollen supplies, which results in incredibly high energy expenditures. The demand for food encourages maximizing the rate of intake, and the high expenses need energy optimization. The fact that foraging occurs in a microclimate with fluctuating food quality and availability must be considered in experiments on how honeybees handle this issue. Here, we describe how honeybee foragers deal with this difficulty in their extremely changeable environment by simultaneous monitoring of energy costs, gains, intake rate, and efficiency. They employ a "investment-guided" (time is honey) economic approach that promises higher profits if possible, during an infinite sucrose flow. By using both their own heat generation and solar heat to raise their body temperature to a point where a high suction velocity is guaranteed, they maximize their net intake rate. When an elevated body temperature would not ensure a high intake rate, they resort to a "economizing" (or "save the honey") optimization of energy efficiency if the food supply restricts the intake rate. In response to environmental fluctuations, honeybees may maximize colony intake rate and maximize foraging efficiency with this adaptable and gradual switch between economic strategies(Stabentheiner and Kovac 2016).

2.1. Flowering Mismatches:

Honeybees' nutrition and hive production may be impacted if plants bloom earlier or later than normal because they may find fewer blossoms to graze on (Bartomeus et al. 2011a). Climate change-induced droughts are becoming more frequent and severe, endangering honeybee nutrition by reducing the supply of blooming plants. The only food sources for honeybees are nectar and pollen from flowering flowers(Barlow and O'Neill 2020).Water stress during prolonged drought, however, significantly lowers floral variety and abundance in bee feeding environments(Clemence-Mkhope 2021). Colonies suffer from insufficient availability to the carbohydrates, proteins, lipids, vitamins, and minerals needed to promote brood-rearing, create honey storage, and sustain immunity when there are fewer viable plant species in bloom (Wright, Nicolson, and Shafir 2018). Individual and colony-level bee health is harmed by the interaction of these drought-induced dietary deficiencies with additional stressors like parasites and insecticides.

Numerous studies have found a clear correlation between declining floral covers and drought severity. For instance, compared to locations with normal rainfall, those with severe drought had 65% less bloom density(Sidemo Holm et al. 2021). Similarly, flower species richness declined by over 50% during extreme versus moderate drought years in South African grasslands(S. Khalifa et al. 2021). The ensuing flower blooms of moisture-sensitive wildflower species that bees prefer to graze on are greatly reduced by even short dry spells of one to two weeks(Baude et al. 2016). In general, climate forecasts indicate that many significant bee habitats and agricultural regions would experience increased aridity and decreased growing season precipitation(Baude et al. 2016) .

Changes in climate can reduce the variety of plants in an area, limiting the diversity of nectar and pollen sources and affecting bee health and resilience . (Memmott et al. 2007). Colonies of honeybees are forced to go farther in search of scant or alternative food due to the shortage of floral resources. On the other hand, foraging farther out uses more energy and returns less pollen and nectar overall. Bees from colonies raised on drought-stressed feed are smaller and have lower protein reserves(Kuplik, Kerem, and Angel 2021). Reduced colony buildup and weakened immunity results in higher overwintering losses, leaving fewer resilient pollinators come spring (Matthew Smart ,Jeff Pettis, Nathan Rice,Zac Browning 2016). Reduced bee visitation due to drought stress on floral resources limits pollination, productivity, and quality for crops such as berries, apples, cherries, onions, almonds, and squash(Matthew Smart ,Jeff Pettis,Nathan Rice,Zac Browning 2016). Effects on crop blossoms can be lessened by direct watering. Reducing drought frequency through climate mitigation and boosting floral variety at larger scales through habitat restoration are eventually necessary to maintain robust bee populations.

3. Extreme Weather Events.

Honeybees are impacted both directly and indirectly by the increased frequency and severity of extreme weather events including storms, droughts, and floods: The supply of feed can be diminished and habitats destroyed by extreme weather. Colony losses may result from storms or flooding causing physical harm to hive. For honeybees, increased precipitation unpredictability due to climate change presents serious foraging issues. Bees are unable to fly out to gather pollen and nectar during extended periods of intense rain. Because they are unable to control their body temperature when flying in chilly, damp circumstances, honeybees avoid foraging in rainy weather(Crone, Biddinger, and Grozinger 2022). Bees that become chilled and soaked are likely to die, creating selective pressure to avoid exiting the colony during rains(Vaudo et al. 2015). Because of this evolutionary adaptation, which formerly guaranteed colony survival, bees are now in danger from increasingly intense rains. Before their food supplies are severely exhausted, modern honeybee colonies may survive for one to two days without foraging(Couvillon, Schürch, and Ratnieks 2014). However, current climate models predict that in many areas, the frequency and intensity of heavy rainfall would dramatically rise(Easterling et al. 2017). Colonies are increasingly forced to endure up to a week without proper sustenance due to back-to-back downpours of more than two inches every day (Otto et al. 2016) . Developing brood suffers immediate setbacks, while food reserves dwindle. Colonies are already weakened by pesticide exposures or mite infestations often cannot recover once intense rains subside (Kerekes, Mackell, and Elsayed 2025).

Numerous studies have directly connected significant regional losses in honeybee colonies to multi-day periods of intense rainfall. For instance, nearly 50% of managed hives were destroyed by unexpected late spring deluges on the Yucatan Peninsula, which prevented flying for five to seven days during crucial early season forage(Döke, Frazier, and Grozinger 2015). Similarly, a week-long rainy period in Ontario, Canada correlated with 25% colony loss due to starvation when bees could not leave hives(Guzmán-Novoa et al. 2010). When fresh immigration is stopped, honey stocks and pollen supplies gathered in the previous season only survive so long. Seasonal differences in flower availability connect with these rain-induced nutritional deficiencies. Since fewer flowers are in bloom than in the summer, torrential downpours in the early spring and late fall are particularly harmful(Otto et al. 2016). Colonies are unable to store enough honey for overwintering or to strengthen themselves following winter due to extreme rains and a lack of food sources. Risks are increased for hives that are more exposed and isolated, suggesting that landscape elements like fodder diversity and quality moderate the effects of precipitation extremes(Guzmán-Novoa et al. 2010).

Rainfall-limited bee foraging has the potential to directly affect agricultural yields and farmer incomes through lost pollination services and honey production. Pollinators are beneficial to over 75% of the world's most important crops(A. M. Klein et al. 2007). In crops including almonds, apples, blueberries, cucumbers, and onions, prolonged rains limit bee movement among flowers, which lowers fruit set, reduces seed generation, and stunts development(Johansson 2020). When weather conditions limit even managed bees, adding commercial hives only partially compensates. The necessity for habitat protection and climate adaptation measures to mitigate the effects of rain events on bees and the crops they pollinate is underscored by climate models that predict rising precipitation unpredictability in key agricultural regions.

4. Pests and Diseases.

Climate change influences the distribution and virulence of pests and pathogens:

4.1. Varroa Mites:

Varroa destructor mites pose a serious danger to honeybees and may spread and reproduce more easily in warmer climates(Nganso et al. 2017). Honeybees are more vulnerable to Varroa mites during warmer winters. Climate change-induced increases in winter temperatures provide Varroa mites more opportunities to survive and proliferate, which increases honeybee parasitism. The hemolymph of adult and pupal bees provides the food source for the destructive external parasite Varroa. Usually declining throughout the winter, mite numbers skyrocket in the spring and summer (Yves Le Conte, Ellis, and Ritter 2010).

Warmer winters, however, allow more mites to survive the winter. Buildup in the early spring leads to increased infection rates in the summer. Weakened bee health and colony losses are closely correlated with higher overwintering mite burdens. Bees have wing abnormalities, decreased body weight, and physical harm. Because of cumulative summer reproduction, colonies frequently fail before the fall mite infection peaks(Francis, Nielsen, and Kryger 2013). For instance, a 1-2°C increase in UK winter temperatures was linked to 5–10 times higher springtime Varroa levels(Yves Le Conte, Ellis, and Ritter 2010).

The expense of chemical control for beekeepers is further increased by inadequate cold to naturally reduce mites. Dependence on miticides such as coumaphos and tau-fluvalinate promotes mite resistance while increasing pesticide residues in hives(Douglas et al. 2020). Tetracyclines and other antimicrobials are often used in medical, agriculture, and beekeeping. Since tetracycline is the most often used antibiotic in apiculture, honeybee health might be adversely affected by antibiotic exposure(Aljedani 2022).

However, selective breeding shows promise for increasing honeybee grooming behaviors and hygienic traits to better withstand Varroa parasitism even under warmer winters(Büchler et al. 2020).

Risks have increased since Varroa also serves as a vector for several other bee viruses. In bees parasitized by Varroa, diseases such as Israeli acute paralysis virus and deformed wing virus multiply more quickly(Francis, Nielsen, and Kryger 2013). Additionally, warmer overwinter temperatures allow for higher virus loads in colonies. If mite impacts are not controlled, climate change might increase the overall overwinter losses of unmanaged honeybee colonies by as much as 50%(Kosman and Jokela 2019). The consequences for agriculture could be severe, as over 75% of global crop production relies on animal pollination services(A. M. Klein et al. 2007). Expanded mite monitoring and control initiatives will be necessary to maintain robust honeybee populations. However, under increasingly mild winters, mite effects can be reduced by shifting from traditional miticides to integrated pest control and breeding resistant animals.

4.2. Pathogen Proliferation:

Higher temperatures and humidity can enhance the growth of fungal pathogens like Nosema spp., leading to increased disease incidence in bee colonies.

Honeybees are subjected to more frequent temperature extremes and nutritional stress due to increasing climatic unpredictability, which erodes their immune systems. Bees already operate close to their temperature thresholds(Dolezal et al. 2019). Colonies are forced to invest more energy in controlling hive temperature during periods of extreme heat or cold than in boosting individual immunity(Doublet et al. 2015). Extreme weather also reduces foraging chances, which leads to insufficient or subpar nourishment. Individual bee immunocompetence is weakened by malnutrition, which also weakens colony-level defenses against infections(DeGrandi-Hoffman et al. 2016). Colonies are more vulnerable to disease outbreaks because of these interlocking climatic effects. Reduced immunocompetence in bees subjected to heat stress and pollen shortages has been directly shown in a number of controlled investigations. Compared to bees fed a healthy diet, bees on a poor diet showed 60% less expression of genes involved in pathogen defense(Wheeler and Robinson 2014). Bees later infected with Nosema ceranae produced less antimicrobial peptides when exposed to short-term heat stress(Zhang et al. 2017). The biggest obstacle to growing immune responses was the combination of heat extremes and dietary restriction. Immunosuppression at the colony level happens when individual bees are unable to generate enough detoxifying enzymes and antimicrobial peptides. Pathogens can spread amongst nestmates more quickly when social immunity is compromised(Evans and Pettis 2005). Extreme temperatures and poor nourishment stress colonies also display unsanitary practices to get rid of sick brood(Spivak and Danka 2021). In the hive, poor cleanliness creates reservoirs for bacterial, fungal, and viral diseases.

Given the already declining number of honeybee colonies worldwide, interactions between immunity and deteriorating climatic conditions pose serious challenges for agriculture. Pollination by healthy bee populations benefits up to 75% of the world's major food crops(A. M. Klein et al. 2007). If bee disease outbreaks are facilitated by increasingly frequent weather extremes, growers may experience shortages that limit their output. Selective breeding to boost immunological expression and habitat protection to provide a variety of bee food throughout the seasons are necessary to sustain healthy pollinator-dependent crops.

Climate change-induced increases in global temperatures are making honeybees more susceptible to dangerous parasites, infections, and illnesses. The reproduction cycles of many bee diseases are directly accelerated by higher temperatures(Spivak and Danka 2021). Additionally, warmer temperatures impair bees' immune systems, which makes breakouts more likely. Furthermore, greater temperatures allow exotic diseases and parasites to spread into new areas. The appearance and spread of bee diseases are being aided by these contributing variables, underscoring the need for mitigating measures. A major concern exacerbated by climate change is the parasitic Varroa destructor mite. When summer temperatures are at their highest, varroa populations can double in as little as ten days(Y Le Conte and Navajas 2008). To prevent overheating in their hives, bees use vital resources. Reduced sanitary practices in colonies under heat and mite stress accelerate the proliferation of mites(Udousung, Umoh, and Umoh 2022). Additionally, higher temperatures raise Varroa-related virus titters, which increases the number of infections. In a similar vein, bacterial and fungal infections are becoming more common due to climate change. Warmer temperatures result in higher fungal burdens in Nosema ceranae, and heat-stressed bees have compromised immune systems(Gisder et al. 2010). Higher temperatures are implicated in historic expansions of European Foulbrood, enabling these bacteria to emerge as a global honeybee killer(Genersch 2010). As temperatures increased, the ranges for the Israeli Acute Paralysis Virus and the Chronic Bee Paralysis Virus moved poleward(Wilfert et al. 2016).

Other risks to managed European honeybees include Africanized honeybees through range extension caused by climate change and invasions by the Tropilaelaps mite. These tropical parasites and aggressive bee subspecies were formerly contained by the Reduced Winter Cold Limits Act(Y Le Conte and Navajas 2008). However, warming makes it possible for them to expand into temperate climates, which increases the danger of spreading new diseases. Increased disease susceptibility brought on by climate change raises serious implications for pollination services, as honeybee colonies are already declining. Animal pollination is essential for fruit set, productivity, and quality in over 75% of the world's crops(A. M. Klein et al. 2007). Expanded disease monitoring and preventive programs, selective breeding initiatives, and climate mitigation to decrease the circumstances that fuel epidemics will all be necessary to maintain robust, healthy bee populations.

5. Behavior and Phenology.

Behavioral changes in honeybees due to climate change include:

5.1. Foraging Behavior:

Foraging habits can be altered by temperature and flower availability, which may result in decreased efficiency and higher energy costs. Bees' ranges and floral resources vary because of climate change. The geographic ranges of honeybees and the wild blooming plants they depend on for food are changing due to climate change. In order to follow appropriate climate conditions, the livable ranges of flowers and bees shift uphill in elevation and poleward in latitude as temperatures rise(Kerr et al. 2015). But because pollinators and plants react at different speeds, there is a spatial mismatch and the mutualism between the two is disrupted(Pyke et al. 2016). Without deliberate management intervention, honeybees in particular would find it difficult to find high-quality forage supplies in their expanding territories. Range alterations caused by warming have previously been well established. The average latitude of bumble bee species in North America and Europe shifted around 200 miles northward during the course of a century(Kerr et al. 2015). Similar poleward migrations were followed by half of plant species, whereas the other half hardly moved or even shrank equatorward(Freeman et al. 2018). The ranges of plants and bees moved upslopes in mountainous regions, demonstrating altitudinal alterations. As species move more quickly due to climate change, asynchrony is probably going to get worse. The health and survival of honeybees are threatened by spatial mismatches because they result in reduced reproduction, competitive pressure, and nutritional deficiencies(Miller-Struttmann et al. 2015). A steady, varied combination of pollen and nectar is necessary for colonies. They exhibit decreased colony development, heightened vulnerability to illness, and decreased overwintering survival in new regions devoid of known food(Smart et al. 2016). In the absence of vital host plants, solitary bee populations also diminish. Protein supplementation does not make up for the lack of phytochemical variety in honeybee colonies. In agricultural regions that shifting bees have colonized, these dietary constraints interact with other climatic consequences, such as increased exposure to pesticides. By 2100, range changes brought on by climate change might reduce honeybee populations in historically favorable North American and European habitats by as much as 50%(Soroye, Newbold, and Kerr 2020). It will be necessary to increase floral diversity and adapt beekeeping techniques to monitor range shifts in order to sustain bees and agricultural harvests. Which species and areas are most at risk from asynchrony can be determined by further modeling.

5.2. Reproductive Timing:

Changes in climate can affect the timing of mating flights and brood rearing, potentially leading to reproductive mismatches and colony declines.

Concerns about the health of managed honeybees across the world led to the development of monitoring programs. National and worldwide colony loss studies have been carried out by these initiatives, mainly in North America and Europe. The Bee Informed Partnership (BIP) oversees the program's coordination in the US. (vanEngelsdorp et al. 2009), in Canada by the Canadian Association of Professional Apiculturists(Currie, Pernal, and Guzmán-Novoa 2010); 'CAPA – Canadian Association of Professional Apiculturists'), and in Europe by the Prevention of honeybee Colony LOSSes association (COLOSS)(Van Der Zee et al. 2013). Moreover, there are programs in Asia(Tang et al. 2023), in Oceania(Brown et al. 2018) and in Latin America, this last being coordinated by the Latin American Society for Bee Research consortium (SOLATINA)(Requier et al. 2024). In many African countries, beekeeping is still a traditional practice used mainly as a supplementary income activity (Frazier, Muli, and Patch 2024). The findings of the study by(Sibaja Leyton et al. 2025) imply that climatic conditions have a role in Kenya's declining honeybee populations, with precipitation reducing the effects of temperature-induced declines.

However, this practice contributes to food security and poverty reduction by representing a significant diversification of livelihoods(Potts et al. 2016). Together with field research, these monitoring systems discovered categories of risk variables that impact honeybee survival, such climate and beekeeping management (De Jong and Lester 2023). Studies examining the impact of climate on honeybee colony losses are few and restricted to temperate locations, despite the fact that climate has been recognized as a risk factor (Zapata-Hernández et al. 2024). For example, studies from Austria and the Netherlands found a correlation between honeybee mortality and warmer and drier conditions in the previous year(Yasrebi-de Kom, Biesmeijer, and Aguirre-Gutiérrez 2019). Precipitation and temperature had a unimodal association (a negative followed by a positive effect) on colony loss, according to other northeastern US research; the maximum honeybee survival was associated with intermediate values(Calovi et al. 2021).

6. Ecosystem and Agricultural Implications.

Honeybees are integral to pollination, and their decline has broader ecological and economic impacts:

6.1. Crop Yields:

Food security and agricultural output may be impacted by decreased pollination rates caused by declining honeybee numbers. Rainfall-limited bee foraging has the potential to directly affect agricultural yields and farmer incomes through lost pollination services and honey production. Pollinators are beneficial to over 75% of the world's most important crops(A. M. Klein et al. 2007). In crops including almonds, apples, blueberries, cucumbers, and onions, prolonged rains limit bee movement among flowers, which lowers fruit set, reduces seed generation, and stunts development(Yves Le Conte, Ellis, and Ritter 2010). When weather conditions limit even managed bees, adding commercial hives only partially compensates. The necessity for habitat protection and climate adaptation measures to mitigate the effects of rain events on bees and the crops they pollinate is underscored by climate models that predict rising precipitation unpredictability in key agricultural regions.

Farmers' agricultural yields are hampered by declining pollinator numbers. Animal pollination is essential for fruit yield, seed set, and quality for over 75% of globally significant agricultural plants(A. M. Klein et al. 2007). With fewer active bee colonies available after flooding, inadequate pollination lowers yields, decreases fruit sizes, and causes plant defects across crops like apples, blueberries, cucumbers, alfalfa, and soybeans(Yves Le Conte, Ellis, and Ritter 2010). Commercial hives from non-flooded regions provide just a partial buffer when added. Overall, more severe precipitation and sea level rise are predicted by climate models to increase regional flood hazards in coastal and agricultural watersheds(Kundzewicz et al. 2014). Reducing flood vulnerability through better landscape and apiary site selection will be necessary to protect bees to maintain agricultural pollination services.

In agricultural regions that shifting bees have colonized, these dietary constraints interact with other climatic consequences, such as increased exposure to pesticides. By 2100, range changes brought on by climate change might reduce honeybee populations in historically favorable North American and European habitats by as much as 50%(Soroye, Newbold, and Kerr 2020). It will be necessary to increase floral diversity and adapt beekeeping techniques to monitor range shifts to sustain bees and agricultural harvests. Which species and areas are most at risk from asynchrony can be determined by further modeling.

6.2. Wild Plant Pollination:

Many wild plants depend on honeybees for pollination. A fall in bee populations might lead to a reduction in biodiversity and environmental benefit.(Ollerton, Winfree, and Tarrant 2011). Honeybees, or *Apis mellifera*, are vital pollinators of a wide variety of natural flora and agricultural crops. Honeybees are a regulated species that beekeepers relocate across the world because they pollinate $15 billion worth of food crops in the United States alone(Calderone 2012). Animal pollination is essential for more than 90% of wild flowering plant species and more than 75% of the world's primary food crops(A. M. Klein et al. 2007). This significant contribution to the food supply and terrestrial biodiversity depends on healthy bee populations. But a variety of environmental stresses, including climate change, are making honeybees more and more vulnerable(Alaux et al. 2010).

Pollination services, which are necessary to preserve wild plant populations and sustain crop harvests, are under risk due to the effects of warming on honeybees. Insect pollination benefits 87.5% of blooming plants and up to 35% of food crops worldwide(A. M. Klein et al. 2007). Many pollinator-dependent crops, such as apples, cherries, squash, and almonds, produce less fruit and seeds when bee numbers and foraging rates decline(Bishop et al. 2016). Without sufficient bee visits, farmers may experience reduced yields, smaller fruit sizes, and more distorted output. Temporary respite is offered by supplementing commercial honeybee hives, however availability and drive-up are limited because of climatic influences on large-scale migratory activities. Renting pollination for farmers(White and Dillon 2023). To protect vital pollinators in a warm environment, more study measuring bee temperature thresholds and identifying genetic stock that is heat-resilient will assist direct tactics.

In temperate locations, climate change has caused warming to begin earlier in the spring, pushing floral bloom timetables ahead of bee emergence timelines. This phenological mismatch affects colony building, health, and reproduction by depriving bees of essential early-season feed(Fründ, Linsenmair, and Blüthgen 2010). Flowering plants respond directly to temperature and spring immediately, while bees remain constrained by winter diapause and colony development rates(Ogilvie et al. 2017). Bee populations can be impacted by major nutritional shortfalls caused by even minor timing changes of a few weeks, which can compound with other stresses. For instance, there was a noticeable phenological mismatch in central Massachusetts as flower bloom progressed by more than two weeks but bee emergence time remained constant(Bartomeus et al. 2011b). Apple trees in New York reached full bloom 3-4 weeks before adequate managed bee colonies were present in orchards for pollination(Nagamitsu et al. 2010). Solitary bees also suffered starvation and losses when floral resources appeared before nest establishment(Fründ, Linsenmair, and Blüthgen 2010). Both commercial hives and wild bees are under stress from starvation, reduced colony numbers, and stunted growth in the absence of early nourishment. Without enough spring pollen, queens lay fewer eggs, which restricts colony expansion and all-season foraging ability(Sponsler and Johnson 2015). Forced to forage further or on alternative plants, bees show weakened immunity and reduced hygienic behaviors(Alaux et al. 2010). Additionally, declining bee populations reduce pollination redundancy, raising the risks to agricultural productivity. For fruit set and quality, about 75% of the world's most important crops rely on insect pollination(A. M. Klein et al. 2007). Until bee food is naturally abundant, bridge resources may be provided by techniques like supplementary feeding or making sure floral strips have species that bloom sequentially. To maintain diversified pollinator populations, it is still imperative to mitigate climate change to realign bee and flower phenology at scales larger than farmlands.

- **Mitigation and Adaptation Strategies:**

Mitigating the effects of climate change on honeybees involves a combination of habitat protection, sustainable practices, and research. Here are some effective strategies:

1. Habitat Preservation and Restoration:

Protecting and restoring natural habitats to ensure diverse and abundant forage sources(Potts et al. 2010). Protecting and restoring natural habitats ensures bees have access to diverse floral resources, which are critical for their survival as climate patterns shift. Habitat loss exacerbates stress on bee populations, especially under climate change pressures(A.-M. Klein et al. 2007).

2. **Planting Climate-Resilient Floral Resources**:

Introducing native, drought-tolerant, and bloom-varied plant species enhances food security for bees during periods of climatic variability and extreme weather events(Qsbdujdf 2006).

3. **Reducing Pesticide Use**:

Limiting exposure to harmful agrochemicals helps improve bee health and resilience to climate stressors, as pesticides can weaken immune systems and increase mortality.(Goulson et al. 2015).

4. **Implementing Climate-Resilient Beekeeping Practices:**

Adjusting hive management, such as providing shade, water, and protection from temperature extremes, helps maintain hive stability amid changing climate conditions .(S. A. M. Khalifa et al. 2021) .

5. **Supporting Sustainable Agriculture and Agroforestry:**

Promoting practices that increase biodiversity reduce environmental stress on pollinators and enhance ecosystem resilience to climate change. Implementing agricultural practices that support bee health, such as planting cover crops and reducing pesticide use(Puranik, Akbar, and Ghagane 2023).

6. **Research and Genetic Improvement:**

Developing and promoting honeybee strains that are more resilient to climate extremes and diseases. Developing bee strains resistant to temperature extremes, pests, and diseases helps sustain populations under climate stress. Ongoing research improves understanding of adaptive strategies .(Ostiguy et al. 2019).

7. **Public Education and Policy Advocacy:**

Raising awareness and shaping policies are essential to enforce protective measures for bees and mitigate climate change impacts. Community involvement amplifies conservation efforts.(Potts et al. 2010) .

8. **Reducing Carbon Footprint:**

Supporting renewable energy and sustainable consumption reduces greenhouse gas emissions, addressing the root causes of climate change affecting bee habitats .(Martén-Rodríguez et al. 2025).

Conclusion

The physiology, behavior, and ecology of honeybees are all impacted by the complex and profound effects of climate change. Comprehensive approaches including environmental preservation, sustainable farming methods, and continuous research are needed to address these issues. In addition to ensuring their survival, protecting honeybees is essential for the larger agricultural and ecological systems that rely on their pollination services.

Competing Interests

Authors have declared that no competing interests exist.

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