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Buzzing Guardians: Protecting Pollinators in Agricultural Landscapes

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Abstract

In agriculture crop ecosystems, pollination is the foremost fundamental activity performed by fascinating creatures like bees, butterflies, hoverflies, birds, and bats, ensuring reproductive success in angiosperms. Currently, most pollinators appear in red data books as their population and abundance deplete in the ecosystems. Threats like habitat loss, climate change, urbanization, use of chemical pesticides, pests, and diseases drove their extinction. The decline in the pollinator population may considerably decrease global food production and productivity. Effective and efficient conservation strategies are the key elements to mitigate the threats faced by pollinators in the promotion of pollinator resilience. Here, we explored various conservation strategies that restore the pollinator habitat by following sustainable agricultural practices and some policy interventions. Public awareness and collaborative efforts among governments, NGOs, and the private sector are crucial for successfully implementing and adapting these conservation strategies. By acclimatizing an integrated, collaborative, and convincing approach to pollinator conservation, we can assure and predict ecosystem sustainability and productivity, which eventually supports biodiversity and food security.

Introduction

Pollinators are vital creatures that provide multiple essential ecosystem services like pollination, environmental safety, culture, and aesthetics, but they are declining vigorously in this dynamic world (Katumo et al., 2022). Living organisms, mainly bees, bats, birds, beetles, moths, hoverflies, wasps, thrips, and butterflies, are referred to as essential pollinators and contribute 30% of global food production (Khalifa et al., 2021). Pollination by animals enhances global crop production with a value of USD 235-577 billion annually, and the greatest economic benefits have been seen in the Mediterranean, Southern and Eastern Asia, and Europe (Potts, 2016). In India, it is estimated that the direct contribution of insect pollination to agriculture is around INR 22.52 billion annually. In agriculture, using honeybees for pollination is considered a micro-concept and impacted as a "macro-economic" factor (Chaudhary & Chand, 2017). Several threats to pollinators negatively impact their natural habitats, diversity, health, abundance, and population viability. This article presents the significant threats to the pollinators, initiatives across the globe to mitigate the threats, and strategies to conserve the pollinators. The main objective of this review is to educate peers and policymakers on adopting pollinator conservation measures in agricultural landscapes with a participatory approach.

General Pollinators and Benefits

Pollination is the transfer of pollen within or between flowers to allow fertilization and seed production with the help of biotic and abiotic agents. The process of pollination

is mediated by several abiotic (Wind – Anemophily, Water – Hydrophily) and biotic agents (Bees – Melittophily; Bats – Chiropterophily; Birds – Ornithophily; Beetles – Cantharophily, Moths-Phalaenophily; Flies – Myophily; Butterflies – Psychophily). In agroecosystems, only 15% of crop plants depend on domesticated bees; the rest, wild bees and other wildlife pollinate 80% of crops. Pollinators provide pollination services for 180,000 plant species and more than 1,200 food crops. It is estimated that one out of every three bites of food we eat is there because of the activity of pollinators (Klein et al., 2007).

Importance of insect pollinators

Insect pollinators like bees, flies, butterflies, and beetles help pollinate most crops. Entomophily plays an important role in increasing the seed set and yield of the crops, as depicted in Table 1.

Threats for pollinators

Some critical threats to pollinators' survival include increasing habitat loss and fragmentation, climate change, expansion of invasive species (including non-native honey bees), chemical pesticides, urbanization, monocropping, pests, and diseases.

Table 1. List of pollen and nectar reward yielding plants to the bees.

Sl. No	Floral rewards	Examples
1	Pollen	Maple, Grey halder, Chest nut, Hack berry, Flowering quince, American hazel, Haw thorn, White ash, American holly, Walnut, Tulip tree, Crab apple, Apple, American sycamore, Plum, Almond, Cherry plum, Sour cherry, Peach, Black cherry, Black thorn, Pear, Oak, Black berry, Rasp berry, Willow, Winged elm, Common bugle, Asparagus, Mustard, Canola, Yellow crocus, Winter aconite, Snow drop, Common mallow, Sweet clover, Sainfoin, Dandelion, Gorse, White mustard, Chick weed, Blue beard, Virginia creeper, Elder, Linden, Onion, Aster, Marigold, Hemp, Melons, Pumpkin, Cucumber, Buckwheat, Sunflower, Jewel weed, Lupin, Alfalfa, Sweet clover, Basil, Sweet corn, Ivy, Golden rod, Eucalyptus, Niger, Cuphea, Basil, Coral creeper, Jowar, Maize, Pomegranate.
2	Nectar	Maple, catalpa, hack berry, American holly, tulip tree, Apple, Pear, Black cherry, Sumac, Black locust, Rasp berry, Black berry, Willow, Bee bee tree, Bass wood, Sour wood, Anise hyssop, Milk weed, Pongamia, Eucalyptus, Acacia, Rubber, Aster, Mustard, Sunflower, Rapeseed, Mountain fluet, Viper's bugloss, Globe thistle, Firewood, Heather, Soybean, Basil, Sweet clover, Alfalfa, Clover, Phacelia, Smart weed, Self heal, Golden rod, Cuphea, Dandelion, Thyme, Clover, Sesame, Niger, Coral creeper, Cotton, Mesta, Lucerne, Banana, Mandarin, Cashew.
3	Pollen and nectar	Maple, American holly, Apple, Pear, Black cherry, Rasp berry, Black berry, Willow, Milk weed, Eucalyptus, Clover, Mustard, Sunflower, Niger, Alfalfa, Cuphea, Golden rod, Basil, Aster, Coral creeper, oilseeds, pulses, Berseem, Chilli, Coriander, Fennel, Cumin, Orange, Guava, Litchi, Cherry, Onion, Drumstick and Cucurbits.

1. Habitat loss and fragmentation

Habitat loss is defined as the deterioration of habitat to the point where it can no longer support the species and biological groups living naturally there. Habitat loss and fragmentation are the significant factors in the decline of the pollinator population. The loss of natural terrestrial habitat has negatively influenced bee populations in the prairies of the Northern Great Plains, and roads constructed by habitat destruction negatively impact social bees (Marika, 2021). Edges of roads act as barriers to the movement of bees (Bhattacharya et al. 2003), which increases the mortality and predation risk of bees (Hadley & Betts, 2012) and alters vegetation structure (Rodgers & Koper, 2017). Roads also alter habitat quality by increasing noise, air pollution, and salt concentrations (Fahrig & Rytwinski, 2009). Habitat destruction by unregulated mining affects the abundance and diversity of pollinators (Addae et al., 2024). The widespread conversion of bees' natural habitats into agricultural landscapes has destroyed adequate nesting sites and the floral diversity of bee species. Large monocultures with intensive agriculture production systems often cannot support the populations of wild bees (particularly species with short foraging ranges) (Kline et al., 2020).

Habitat loss and fragmentation drastically alter the structure of the plant-pollinator interaction network by changing the quantity and identities of interacting species. Fragmentation of the land resulted in the loss of rare and sensitive species, which reduced various mutualistic interactions and the total size of a network. It also altered the composition of pollinator and plant communities by favoring disturbance-tolerant and edge-associated species, driving mutualists to seek new or less desirable partners (Gonzalez et al., 2011). Specialized plants and pollinators in a mutualistic network are more prone to habitat loss and fragmentation because, unlike generalists, they cannot switch or replace their mutualistic partners by denying the specific interaction (Xiao et al., 2016). Disruption of plant-pollinator mutualism affects the floral visitation pattern by the bees due to pollen limitation, their nesting behavior, and ultimately, the seed set and yield of crops (Fabienne & Johnson, 2004).

2. Climate change

Climate change poses various challenges for pollinators in this 21st century (Settele et al., 2016). Climate change has diverse effects on pollinators, including shifts in the species

range, alter in the phenology, changes in physiological processing rates, altered species interaction, changes in diversity, quality, and quantity of floral resources, habitat loss, and pathogen exposure (Scaven & Rafferty, 2013).

Global warming contributes significantly to pollinators' rapid disappearance, like bees (Andrews, 2019) and butterflies (Van Strien et al., 2019). Climate change is a leading threat to pollinators due to eventual temperature increase or the increasing frequency of extreme events. The intensity of extreme weather events affects food sources, habitats, and essential conditions on which pollinators rely for survival. In particular, the International Union for Conservation of Nature (IUCN) lists 16 species of bees as vulnerable, 18 as endangered, and nine as critically endangered globally.

Climate change caused a temporal shift in the anthesis period, causing a mismatch with the occurrence of bees and negatively affecting pollination (Freimuth, 2022). With increased temperatures due to climate change, the sugar content in the nectar was reported to decrease, thus reducing the nutrient content and the palatability of the nectar for the bees (Takkis, 2015). This leads to a decline in pollinators' health and reproductive success, as well as in pollination of plants (Descamps et al., 2021). Warmer winters result in lower survival of bee species that overwinter as adults (Rajagopalan et al., 2024). Unseasonal warmer winters increase the metabolism of the bees as they burn more calories at a faster rate, impacting their foraging activity (Prado et al., 2022)

Heat stress (even a short exposure of < 1 hour at 36 ºC) significantly affects reproduction and fertility. Heat-induced sterility has been reported in Diptera and Hymenoptera (Walsh et al., 2019). Altered rainfall patterns change the timings of phenological phases, resulting in pollen degradation and nectar dilution, which detrimentally affects the fitness of the plants and pollinators (David & Sean, 2019).

Severe droughts in India led to fruit abortions in fig trees, as there was a local extinction of fig wasps during this period (Soubadra et al., 2018). In 2023, 60% of western monarch butterflies died in California due to severe rain and wind storms (James, 2024). Extreme flooding caused a lethal effect on soil-nesting bees by depriving them of oxygen levels (Fellendorf et al., 2004).

Bees need water for various activities, such as hive cooling and honey dilution. Bee colonies will suffer less accessibility to clean water due to climate change. (Heglandet al., 2009). Storms like hurricanes and tornadoes physically harm the beehives and shift the colonies from established positions. Such interruptions for the beehives result in the loss of bees and floral resources (Vergera, 2023). The influence of climate change on the morphological and physiological traits of bees affecting their tongue length and body size was well reported. This may affect their mechanical fitness in the flowers, affecting the plant-pollinator interactions (Corbet, 2000).

3. Monoculture

Monoculture is defined as cultivating a single type of crop or single crop species on large scales to maximize profit. Monoculture in the agro-ecosystem leads to a lot of inapt problems listed below;

- **Nutrition deficiency**: In monoculture, only one type of pollen is available as a food source for bees, leading to nutritional deficiency in bee colonies, affecting the brood's health to a greater extent (Naug, 2009). Bees feeding on monofloral pollen in monoculture pasturage were reported to affect the gut microbiota, negatively impacting the bees' immunity and making them vulnerable to the microbial pathogen *Nosema ceranae* (Castelli et al., 2020).

- **Limited bloom time**: Most crops in a monoculture have shorter blooming times, which shortens nectar and pollen available during the short period of anthesis. After the cessation of the anthesis period, the foragers may starve for the resources that may dwindle the pollen/nectar storage in the bee colonies, often leading to migration and loss of colonies. Higher rates of absconding occur in the colonies of *Apis mellifera secutellata* due to the seasonality of bee flora with a limited bloom period (Shitaneh et al., 2022). Alaux et al. (2010) reported that monoculture pastures do not provide the bees with a sustained and necessary pollen supply for their survival and colony growth. Toshack & Elle (2019) reported that blueberry pollen has low crude protein content and lacks amino acids essential for the bees. The duration of blueberry flowering lasts for a period of three to four weeks during the spring, providing insufficient floral sources to the foraging bees.

- **Bees' Poor immune systems:** when fed on multifloral pollen, bees have a broader diet range that will contribute to developing healthy brood and fit foragers with robust immune systems. Bees feeding on unifloral pollen under monocropping conditions will have a narrow diet that will impair the healthy immune system, increasing their susceptibility to pests and diseases. The impact of pollen quality on the physiology of the nurse bee and the survival of healthy bees was well reported (Pasquale et al., 2013). The development of the bees that consumed polyfloral pollen was 2.8% faster than those that relied on unifloral pollen. In addition, the bees that foraged on poly pollen gained more cocoon weight. i.e., 5.9% than the bees foraging on single pollen (Schwarz et al., 2024). Micro-colonies of bumble bees that fed on polyfloral pollen with and without pesticide contamination gained more weight and exhibited higher reproductive efforts; polyfloral micro colonies produced four times more males and had 1.5 times more brood (larvae and pupae) than unifloral pollen. These findings proved that the bees that feed on polyfloral pollen, even with pesticide contamination, exhibited more survival potential with developed innate immunity (Dance et al., 2017).

4. Expansion of invasive species (including non-native honey bees)

Bees provide vital ecosystem services as pollinators, ensuring the reproductive success of angiosperms. The expansion of invasive species threatens the natural balance of this vital pollination service rendered by the bees. Introducing non-invasive species of bees affects ecosystems' interconnectedness, the foraging patterns of honeybees, and competition for floral resources. Native bees may exhibit non-preference towards the invasive plants, rendering their activity and survival at stake. The increased competition for nectar and pollen can lead to variations in flight paths and reduced accessibility to vital food sources by impacting the health of bee colonies (Russo, 2016). The invasion of non-native bees resulted in peak competition for their nesting sites and shelter, which is owed to the displacement of native bee populations (Chapman & Oldroyd, 2020). Non-native bee species also act as carriers for harmful diseases of honey bees. The spread of diseases from non-native bees increased the susceptibility of bee populations, potentially triggering colony collapse disorder (Goulson, 2003). Interbreeding between native and non-native bees leads to genetic dilution within native bee populations. Then, genetic dilution impacts the adaptability and resilience of bees, potentially reducing their ability to withstand environmental stress (Belsky & Joshi, 2019). The hornet *Vespa* sp. was introduced to Europe and North America as a potential predator to control forest caterpillars. As time proceeds, these wasps evolve as a threat, invading the colonies of western honeybees and attacking the weaker colonies. Consequently, the number of colonies and honey production in commercial beekeeping in Europe and North America (Cappa et al., 2021). In the European countries invaded by *V. velutina*, *A. mellifera* colonies face its impact year after year, with reported losses of at least 20–30%. The wasp hunts for the hive, returning foragers by hovering in front of the entrance, grabbing the bees in flight, and killing them with their jaws. The adult wasp carries the killed bees' thorax region to provide the protein-rich mass to her broods (Laurino et al., 2020).

The turf grass lawns in urban landscapes and non-native plants or plants that have not historically been part of a particular region negatively impact the abundance of floral resources for bees, flies, butterflies, and birds to forage and reproduce. In most cases, pollinators do not prefer cultivars and hybrids of invasive plants and exotic plants because of their double flowers, color pattern, and sterile flowers with zero pollen. Westrich (2015) reported that a sterile hybrid is the exotic shrub forsythia (Forsythia x intermedia), which produces countless flowers but without pollen and nectar during the spring season in California. Furthermore, the expansion of lawns reduces the species richness of plants and the biodiversity of developed areas.

5. Urbanization

Urbanization is defined as an increase in the population density in urban areas due to the growth of cities and towns accompanied by industrialization and modernization. This brings a significant change in the social, environmental, and economic status of people. From an environmental perspective, urbanization depletes the resources and leads to pollution, habitat destruction, loss of biodiversity, and destroying species interactions and the natural functioning of the ecosystem.

The plant-pollinator interaction was influenced by the degree of urbanization and the quality of the local habitat. Though urbanization was reported to increase the abundance of the bees, increased plantings of foliage-type plants without any flora negatively influence the species richness of the bee population. Meanwhile, it negatively influences the flowering plant and pollinator communities (Herrmann, 2023). Urbanization also manipulates phenological events like the migration of birds, reproduction in amphibians, plant growth and flowering, and arthropod appearance and development, which is vital for the reproductive success of angiosperms (Neil et al., 2010).

Urbanization exerts pressure, impacts species interactions, and disrupts the pollinator movement and some aspects of pollinator ecology, like species abundance and distribution, habitat availability, body size, and foraging habits in fragmented urban landscapes (Prendergast et al., 2022). Wing wear, a vital parameter of bee foraging, was significantly higher in the females of *Agapostemon virescens* recorded from the medium-intensity urbanized sites compared to the low-intensity urbanized sites (Brasil et al., 2023). Pfeiffer et al. (2021) reported a decreased average bee abundance from 41.7 to 20.8 and average species richness from 17.4 to 11.3 in pre-1960 compared to post-1960 median urban development activities in Madison, U.S.A. He correlated the reduction in bee abundance and species richness, driven mainly by decreases in soil-nesting bees, which decreased abundance from 28.7 to 13.6 bees and 11.3 to 7.6 species from old to newly developed urban areas.

With increased pollution levels, the proliferation of introduced species, and warmer temperatures, plant-pollinator interactions were predicted to face a spatial and temporal shift in the phenomenon (Harrison & Winfree, 2015; Wenzel et al., 2019). Artificial lights at night in urban areas (known now as 'light pollution') negatively impact the bee pollinators by affecting their circadian rhythms and movement activities, impacting the reproductive success of night blooming plants (Knop et al., 2017) and altering the foraging activity of nocturnal pollinators like birds (Dwyer et al., 2013) and bats (Straka et al., 2019).

The sex ratio of the bees was reported to be significantly male-biased as per the theory of conditional sex allocation that presents that under harsher developmental environments

of urban developments, the resultant offspring will be male-biased in nature (Frank & Swingland, 1988). The body size of the bees was significantly smaller in the urban areas due to the paucity of floral resources that impaired their foraging activity and lesser provision to the developing broods in the nests (Chole et al., 2019). Threlfall et al. (2015) reported that the ground nesting activity of *Homalictus* bees was disproportionately affected by the lack of impervious bare ground areas with green cover in the urban areas with more cement and asphalt layered areas.

The effect of urbanization puts way for the accumulation of heavy metals in water bodies. When bees are exposed to contaminated water, it leads to bioaccumulation of toxic heavy metals in the honey, wax, propolis, larvae, and adults of the bees. This results in the deterioration of individual honeybees and whole colony health and survival (Hladun et al., 2016). Plants growing near heavy metal-contaminated water bodies might accumulate toxins in the pollen and nectar that negatively impacts the flower visitation by the bees affecting their navigation abilities (Moron et al., 2014). High daily temperature and poor air quality depletes the functions of genes related to the immune system and oxidative stress in bees (Mayack et al., 2023).

In this modern world, bees are disappearing with the rise in electromagnetic radiation pollution from mobile networks and electronic gadgets. The electrosmog disrupts the navigation capacity of the bees (Sharma & Neelima, 2010). In addition, bees leave the hive and fail to return to the colony as they lose navigation ability and communication as there is disruption in the waggle dance (Ritu et al., 2018). This supports the theory of colony collapse disorder (Santhosh Kumar, 2018). Electromagnetic radiations from the mobile towers detrimentally affect the reproduction and lifecycle of the bees (Nashaat et al., 2013). Meanwhile, the radiation reduces the queen's fecundity honey production (Sharma & Neelima, 2010) and influences the queen to produce more drones in the colony (Ritu et al., 2018).

6. Use of pesticides

Pesticides are the toxic chemicals used in urban and agricultural ecosystems to kill invertebrate pests, diseases, and weeds. Pesticides include insecticides, fungicides, and herbicides, which harm pollinators and other beneficial insects. Pesticide utilization and contamination are widespread in the agro-ecosystems. More than 90% of pollen samples in bee hives of agricultural landscapes and streams are contaminated with more than one pesticide (Mullin et al., 2010). Pollinators are exposed to pesticides in different ways, i.e., i) Direct contact, when bees directly ingest pesticide-contaminated pollen and nectar when pesticides are sprayed on the bee-foraging plants and weeds (Minucci et al., 2021). ii) Residue contact, when pollinators visit flowers or wander on leaves of plants in which they are previously sprayed (Fantke et al., 2018). iii) Nest material is contaminated as the foragers feed on pesticide-contaminated pollen that gets carried over to the brood provision, impacting their growth and development. Butterflies are at risk of pesticide exposure while laying their eggs on host plants treated with pesticides. Solitary bees risk exposure when collecting plant material or soil used to construct nests (Fabio et al., 2018).

There are two ways by which insecticides can kill honey bees. One is direct contact with the bees when they forage in the field. The bee immediately dies and does not return to the hive. In this case, the queen, brood, and nurse bees are not contaminated, and the colony survives. The second and most perilous way is when the bee comes in contact with an insecticide and transports it back to the colony, either as contaminated pollen or nectar or on its body; this affects the whole colony, including the brood and adults.

Organophosphates: Organophosphates are the widely used group of insecticides in agriculture to which the pollinators are exposed during crop pollination. Symptoms of organophosphate poisoning in honey bees include loss of activity, abnormal wobbly movements, lying on the back or spinning while beating wings in this position, and regurgitation of collected nectar. Exposure of the bee colony to microencapsulated methyl parathion or acephate (acetamidophos) damages the brood and queen (Guez et al., 2005). The exposure of wild and domesticated bees to lethal and sublethal doses of O.P. compounds impairs the fitness of wild and managed bees and reduces pollination and food security (Chen et al., 2021). Organophosphorus insecticides like chlorpyrifos and phosmet are highly toxic to stingless bees, *Scaptotrigona bipunctata,* and *Tetragonisca fiebrigi* both topically and by ingesting contaminated pollen and nectar (Dorneles et al., 2017). The exposure to profenophos neurotoxic poison leads to dizziness, paralysis, and death of most of the pollinators and affects the functioning of the ecosystem (Raj et al., 2024). O.P.s like profenophos, chlorpyrifos, malathion, and diazinon were found in pollen collected by *A. mellifera* and honey stored in the colonies. This exposure to contaminated dietary resources causes the threat and lethality to bees (Al Naggar et al., 2015).

Carbamates: Carbamates are widely used chemical insecticides in cropping ecosystems to control significant crop pests. Symptoms of carbamate poisoning in honey bees include an inability of adult bees to fly, dead brood or newly emerged workers, and sublethal effects on queens also recorded, such as poor or erratic egg-laying performance (Halima et al., 2024). Carbofuran impacts negatively on bees' activity and causes mortality of bees, when they forage on contaminated plants for pollen and nectar (Janisse et al., 2005). Consumption of carbaryl-adulterated pollen and nectar affects the antioxidant

capacity of honeybee larvae and the flight ability of adult bees (Gao, 2022). The synergistic effect of N-Methylcarbamate and piperonyl butoxide on *A. mellifera* causes a complete loss of bee colonies (Georghiou & Atkins, 1964).

Organochlorines: Organochlorines are low-degradable toxicants that accumulate in living tissues and are widely banned for use due to factors like 'bioaccumulation' in living systems. In honeybees, organochlorines lead to loss of activity, abnormal wobbly movements, lying on the back, or spinning while beating wings in this position (Jayaraj et al., 2016). Dichlorodiphenyl trichloroethane (D.D.T.) and benzene hexachloride (BHC) are the prominent insecticides in this group. Spraying them on flower blooms causes the death of bees and wild bee populations (Way & Synge, 1948).

Synthetic pyrethroids: Synthetic pyrethroids are insecticides derived from pyrethrins, a natural pesticide found in chrysanthemum flowers. They were found to be more toxic and known for their quick knockdown action with lower breakdown time. They were also formulated with synergists to increase potency (Thatheyus & Deborah, 2013). The exposure of bees to chemicals like cyfluthrin, tau-fluvalinate, allethrin, and permethrin and nectar toxins like aconitine and grayanotoxin I affects their locomotion, grooming, and wing fanning behavior. Nectar toxin, aconitine, and the pyrethroid allethrin were reported to reduce the antennae grooming time due to contact with bees (Oliver et al., 2015). Insecticides like cyfluthrin and lambda-cyhalothrin are also found to be highly toxic to honey bees by deterring their normal activities and causing death (Johnson et al., 2006). Synthetic pyrethroids like permethrin and cypermethrin act as repellants for forager bees and reduce the foraging activity (Rieth & Levin, 1988). Exposure to bifenthrin and deltamethrin reduces the fecundity of the bees and alters the immature development period (Dai et al., 2010).

Neonicotinoids: Neonicotinoids are systemic in action and have been reported to cause direct and sub-lethal poisoning in bees, drastically affecting colony performance. Imidacloprid impairs the ability to learn floral associations and affects the learning performance of bees (Muth & Leonard, 2019). Seed treatment of oilseed rape with neonicotinoids impacts the long-term population of wild bees (Woodcock et al., 2016). Using neonicotinoids reduces the survivability of honeybee drones, increases the drifting behavior of non-maternal colonies, and delays flight activities with a reduction in sperm count in the drones (Straub et al., 2021). Clothianidin detrimentally affects the immune system of bees and promotes the replication of deformed wing virus in honey bees (Di Prisco et al., 2013). Consumption of thiamethoxam-contaminated pollen and nectar increases the movement toward the light and deteriorates the colony's health by harming workers' locomotion. Meanwhile, acute and chronic exposure to thiamethoxam potentially alters the division of labor during foraging and indoor activities (Tosi & Nieh, 2017).

Fungicides: Fungicides are a group of chemicals used to eradicate the disease-causing fungi infesting different crop plants. In fruit cropping system (Pear, Peach, cherry, and sweet crabapple), spraying Mancozeb and Penthiopyrad during anthesis was reported to cause survival ability negatively impacting the health of solitary mason bees, *Osmia cornifrons* (Porras et al., 2024). O Neal et al. (2019) reported that foraging bees (*A. mellifera*) exposed to Chlorothalonil carry the residue in the rewards to brood food. The brood larvae fed on the contaminated brood pollen were reported to be susceptible to viral infection with decreased social immunity and deformed wings. Long-term exposure to pyraclostrobin by the forager bees of *A. mellifera* reflects in decreasing nutrient metabolism and immune competence and desperately affects the growth and development of honeybees (Xiong et al., 2023).

Herbicides: Herbicides are also known as chemical weed killers, and they are used to destroy undesirable vegetation in desirable areas like farm fields, parks, and gardens. Glyphosate negatively affects the associative learning processes of foragers, the cognitive and sensory abilities of young bees, and delays brood development (Farina et al., 2019), besides affecting the gut microbiota and innate immunity by decreasing the expression of some antimicrobial peptides and inhibits melanization of the bee hemolymph (Motta et al., 2022). Foraging on 2,4-D sprayed plants significantly reduced the xenobiotic detoxification gene, *cytochrome P450* in bee larvae, and the foraging activity of adults (Macri et al., 2021).

7. Pests and pathogens

Pests and pathogens significantly impact pollinators, affecting their health, behavior, and populations. These impacts considerably affect ecosystems and agricultural productivity, as well as pollination and seed formation. Insect pests like wax moths, hive beetles, and mites threaten bees by disrupting their foraging activity, destroying the colony, and transmitting viral infections (Kushwaha et al., 2023). Diseases like nosemosis, American foul brood, European foul brood, Sacbrood virus, and deformed wing virus pose a contagious effect on gut health and the immune system (Muhammad & Shah, 2024).

8. Colony collapse disorder

Colony Collapse Disorder (C.C.D.) is characterized by the sudden and unusual disappearance of worker bees from a hive, leaving behind the queen, capped and uncapped brood, and a hive full of honey and pollen. The main factors responsible for C.C.D. include infection with varroa mites, usage of pesticides, viruses, farming practices, monoculture, unhygienic hive, climatic factors (U.S.D.A. 2007), electromagnetic waves (Warnke, 2009) and genetically modified organisms (Malone & Pham-Delegue, 2001).

General conservation strategies to protect insect pollinators

a. Protect natural habitats: The priority of the conservation of pollinators is to identify and protect the existing natural pollinator habitat. We must grow potential insect-pollinated crops, flowers, and weeds for pollen and nectar in roadsides, forest edges, hedgerows, fallow fields, and buffer areas. Farm planning must be done to provide year-round forage for pollinators by growing pollinator potential crops. Adding non-cropped habitats with nectar-yielding plants can increase the numerical abundance of the bees in crop ecosystems (Wratten et al., 2012). Noxious and invasive plants not visited by bees must be removed from the protected areas. At the margins of protected natural habitat, an effort must be made to plant very early and late blooming plants. Early flowering plants reward bees emerging from hibernation, whereas late flowering plants provide food for bumble bees to reserve the energy to enter winter dormancy (Pywell et al., 2005). Solitary bees prefer to construct nests in hollow cavities, tree holes, crevices in the walls, fallen flowers (Amala et al., 2017), pithy stems (Amala & Shivalingaswamy, 2019), hollow petioles of different plants (Amala et al., 2019) have been reported. Filipiauk (2019) reported that wild bees need undisturbed nesting cavities in the ground, hollow stems, twigs, and appropriate floral resources for growth and development. Natural nesting sites of cavity-nesting solitary bees need to be identified and conserved to favor the natural multiplication of solitary bees. Feral colonies of bees are treasures with built-in stores of pollen and brood accumulated over the years. There is a need to develop sustainable multiplication strategies for the feral colonies to avoid indiscriminate destructive hiving of the colonies. Amala et al. (2023) developed a sustainable eduction technique to hive and multiply feral colonies of stingless bees without loss in perennial colonies. Some potential crops with their rewards, like pollen and nectar, are given in Table 2.

Table 2: Increase in yield of crops with the involvement of the pollinators.

Sl. no	Crop	Pollinators involved	Percentage yield increase (%)	References
1	Sunflower	Honeybees and solitary bees	79	Mohapatra et al., 2010
2	Mustard	Honeybees	55	
3	Niger	Honeybees	33	
4	Sesamum	Honeybees	15	
5	Safflower	Honeybees	64	
6	Litchi	Honeybees	20	
7	Coconut	Honeybees	40	
8	Gourds	Honeybees	20	
9	Apple	Honeybees, wildbees, bumble bees and stingless bees	19.5	Mohapatra et al., 2010; Mallinger & Gratton, 2015; Bonneau et al., 2021; Viana et al., 2014
10	Oil tree peony	Bees	56.28	Zhang et al., 2022
11	Fennel	Hoverflies	104.9	Sanchez et al., 2022a; Amala et al., 2023
12	Cotton	Honeybees and wildbees	62	Stein et al., 2017
13	Mango	Hoverflies and honeybees	240	Sanchez et al., 2022b; Deuri et al., 2018
14	Radish	Honeybees	22-100	Bartomeus et al., 2014
15	Cabbage	Honeybees	100-300	
16	Oilseed rape	Honeybees	30	
17	Leguminosae, Verbenaceae, Rubiaceae	Butterflies		Bhandari et al., 2021
18	Strawberry	Honeybees and European orchard bee	20	Bartomeus et al., 2014; Herrmann et al., 2019
19	Cucumber	Honeybees and stingless bees	10	Morse & Calderone, 2000; Azmi et al., 2017
20	Sweet pepper	Bumble bees	49.8	Serrano & Guerra-Sanz, 2006
21	Cumin	Honeybees	41.37	Meena et al., 2018
22	Coriander	Honeybees	69.51	Patil & Pastagia, 2016

b. Habitat restoration: High-quality foraging habitats can be made in the form of pollinator meadow models with abundant pollen and nectar, i.e., bee pasture (Fig 1) and pollinator gardens (Fig 2), orchard understory plantings, windbreaks, hedgerows, and flowering cover crops. Mixtures of native and non-native plants must be grown if non-native species are naturalized. We can restore the natural habitat by establishing a diverse mix of plants to ensure the year-round availability of floral rewards for pollinators and hosts for pollinator groups. The size of the restored habitat must be one acre to two acres to get maximum benefit (Kremen et al., 2004; Morandin & Winston, 2006).

c. Protect the ground nesting sites: Few pollinators are ground nesting in nature; they complete their life cycle in the ground by making tunnels with special knowledge. Ground nesting bee, *Hoplonomia westwoodi,* prefers to nest in ground-built subterranean nests on a leveled soil surface with turrets and the main shaft running to a depth of 70.1 cm (Amala & Shivalingaswamy, 2018). Cane (1991) reported that ground-nesting bees prefer constructing nests in sandy soils. With the increase in the survival risks, the population of ground-nesting bees is declining progressively. Some measures have to be followed to conserve the ground-nesting bees are:

Fig 1. Bee pasture maintained in the view of conservation of pollinators at ICAR-NBAIR, Bengaluru.

Fig 2. Pollinator garden located at ICAR-NBAIR, Bengaluru.

i) Avoid tillage (Shuler et al., 2005) and flood irrigation in the barren and cropped areas occupied by ground-nesting bees (Vaughan et al., 2007).

ii) Discourage grazing in the grasslands, which helps in the undeterred activity of ground-nesting bees (Buckles & Harmon 2019).

iii) Apply pesticides using a need-based approach to conserve ground-nesting bees (Christmann, 2022).

d. Pesticide mitigation measures

The Environment Protection Agency (EPA) identified considerable risks pollinators face from using registered pesticides. The mitigation measures suggested by the EPA. to conserve pollinators are:

i) Restricted use of pesticides during the growth and blooming period of plants as the activity of pollinators will be more during the anthesis stage.

ii) Reduce the application rate and avoid daytime spraying of pesticides, as most of the pollinators are active during the day.

iii) The ground and aerial buffers should be developed in the established area of the pollinator habitat, and the use of pesticides should be disallowed in these conserved areas.

iv) Prohibit the usage of pesticides on potential target crops of pollinators.

v) Reduce spray drift and residue toxicity by setting a maximum wind speed when spraying will happen, lowering the application height for boom and aerial sprayers, and selecting nozzle sizes that deliver larger droplets.

Integrated Pest and Pollinator Management (IPPM):

Integrated Pest and Pollinator Management (IPPM) is a comprehensive method that integrates pest management with the conservation of pollinators. It seeks to mitigate the detrimental effects of pest control tactics on pollinators, which have a crucial role in pollinating most crops and maintaining a sustainable ecosystem. The main aim of IPPM is to balance agricultural productivity with the conservation of pollinators such as bees, butterflies, and other insects (Lundin et al., 2021). Integrated Pest and Pollinator Management highlights the importance of judicial use of selected pesticides and other pest management practices that possess the least and tolerable impact on habitats, habits, reproductive potential, fecundity, foraging behavior, survival ability, growth and development of pollinators (Mukhtar et al., 2023). Amala et al. (2022) reported that providing bamboo trap nests to conserve leaf cutter bees in pigeon peas also served as nesting habitats for potter wasps, *Rhynchium brunneum brunneum* that provide the natural reduction of borers pests in pigeon peas.

Case study of IPPM in pear crop ecosystem

Pear is an important fruit grown in all the temperate countries of the world. Pear growers have adopted most integrated pest management (IPM) strategies in managing pests and diseases. As a part of IPM, the hedgerows are grown around the fruit orchard, which provides a better habitat for pollinators, i.e., 3.5 times more than pear crops (Belien et al., 2021). With this additional advantage of hedgerows, the IPM concept was extended to IPPM in the crop ecosystem (Lundin et al., 2021). In pear crops, the hedgerows attracted more pollinators (31%) than pests (19%). The activity of *A. mellifera*, *Bombus* spp, *Osmia* spp, and other pollinators enhanced the diameter, fruit quality, and yield of the pear. Meanwhile, the mean pear quality index was 83.1 when pollinators were involved and 58.9 when pollinators were not. This case study illustrates the role of hedgerows as an IPM component, supports pollinator richness in the pear ecosystem (Belien et al., 2021), and supports innovative pollinator conservation strategies.

e) Training and education

i) To prepare syllabi for graded training courses from one-day training for amateurs to one-year Post-graduate diploma courses for graduates.

ii) Agriculture colleges and forest guard training colleges must include topics on apiculture to teach and train them for beekeeping.

iii) Agriculture institutes, pollinator conservation clubs, and environmental groups should conduct workshops on creating awareness about pollinator gardens, building bee hotels, and pollinator conservation strategies.

iv) Institutes and organizations must provide hands-on workshops and field days focused on pollinator habitat creation, habitat restoration, and sustainable farming practices without pesticides.

Innovative approaches in the conservation of insect pollinators

a) Domiciliation of bees

Studies on artificial domiciliation of solitary bees conducted by A.I.C.R.P. on honeybees and pollinators in India indicated that bundles of paddy straws of 4 to 6 mm diameter cavity and 15 cm length were preferable to the solitary bees for their nest construction. Similarly, paper roll bundles of 0.8 cm to 1 cm installed at 2m height are preferred by leaf cutter bees (*Megachile* sp.) for their nesting. Leonard and Harmon-Threatt (2019) reported using artificial nests to attract solitary bees and increase their natural abundance in agroecosystems. Amala and Shivalingaswamy (2018) reported that bamboo trap nests of 5.0 – 10.0 mm diameter could conserve and augment the leafcutter bee, *Megachile lanata*, in semiurban and urban habitats for their valuable pollination service.

These are the low-cost nesting materials that can be deployed for the conservation of pollinators and to augment pollination services. Gathmann & Tscharntke (2002) reported fourteen species of Apoidea, four species of Sphecidae, one species of Eumenidae, and four species of parasitoids reared from the reed internodes of the grass *Phragmites australis* (Cav.) Trin. ex Steud. (Poaceae). Developing appropriate traps to attract the naturally swarming population of the social bees is paramount to conserving the bees in their natural habitats. Amala and Shivalingaswamy (2021) reported coconut shell traps as appropriate structures to hive the natural swarming population of stingless bees, *Tetragonula iridipennis*. Coconut shell traps, being smaller in size, enable faster settlement of the swarms and aid in better thermoregulation of the nest and further colony development and multiplication.

b) Bee hotels

Bee hotels, also known as bee condos or bee houses, are equivalent to birdhouses (Fig 3). These hotels provide artificial nesting spaces for certain solitary bees and wasps that ordinarily nest in hollow plant stems, crannies, and holes in dead wood. In bee hotels, the nesting habits of solitary bees can be simulated by providing several hollow reeds of *Ipomea*, bamboo (Fig 4), and paper straws. These bee hotels are protected from weather and predators using a variety of structures. Bee hotels support native solitary bees and wasp populations by adding nesting resources to a habitat (Elsa & Meredith et al., 2022). Rahimi et al. (2021) reported that gardeners and farmers used bee hotels to protect the bee pollinators. A nest occupancy rate of 44.1% was recorded in the farms, compared to forests (averaged 30.3%) and urban (averaged 38.3%) environments. Bee hotels are versatile and support solitary bee populations to enhance pollination in agroecosystems. They offer benefits for agriculture, urban biodiversity, and scientific research and promote environmental awareness in the conservation aspects of bees. MacIvor and Packer (2015) documented 27 cavity-nesting bee species that accounted for > 50% of the species in the artificial trap nests in Toronto, Canada. Theodorou et al. (2020) reported an occupancy rate of 7 to 75% by the solitary bees in bee hotels installed in the urban pollinator gardens that were considered 'pollinator hotspots'.

c) Pollinator garden

Pollinator garden is a concept of growing a mixture of annual, biennial, and perennial flowering herbs and shrubs in a protected garden to ensure a year-round supply of pollen and nectar to bees with the aim of in-situ conservation of bees. Conservation of native pollinators will result in enhanced pollination of agricultural and horticultural crops with increased yield. Maintenance of native biodiversity of plants and insects will also result in a balanced ecosystem. Leve et al. (2019) reported that pollinator-friendly gardens should be promoted as a societal response to help mitigate and transform urban environments into bee-friendly habitats. Shivalingaswamy et al. (2020) reported a diverse number of thirty-nine species of bees from the flora of the pollinator garden in Bengaluru, Karnataka, India. Out of the thirty-nine species of bees, nineteen belong to non-*Apis* families, viz., Megachilidae and Halictidae. Anderson et al. (2020) reported a UK-wide citizen science program (BeeWatch) to determine the food plant use by the bumblebee species and identified lavender as the most common plant species widely foraged by the bumble bees to create awareness of native plants preferred by the bees.

Fig 3. Solitary bee activity in Bee hotel at ICAR-NBAIR, Bengaluru.

Fig 4. Hallow bamboo sticks are installed in the sunhemp crop for the nesting of solitary bees.

d) Use of artificial intelligence and machine learning in the conservation of bees

Machine learning (ML) and artificial intelligence (AI) are transformative technologies with broad applications across various fields, including the conservation of bees. These tools offer innovative data analysis, pattern recognition, and predictive modeling solutions and enable more effective and efficient conservation strategies. AI and ML tools are helpful in several ways since they make possible:

- Automatic identification of individual bees by deep learning techniques and analysis of the images and videos to count the bees in colonies.
- Recording bee sounds by sensors placed in the hives. ML analyzes the recordings to detect the changes in the bee sound, indicating stress, disease, pest, and incidence. Early detection helps maintain hive health and stability.
- IoT-based automated devices study the influence of abiotic factors like temperature and relative humidity on bee activity that helps to monitor the beehives for the activity of the foragers, brood volume, and strength of foragers, which helps to adopt forewarning operations for maintaining the hive health (Venkateswaran et al., 2023)
- Identifying areas where habitat restoration will be more beneficial and suggest changes in agricultural practices to protect the pollinators.
- Analyzing massive datasets through AI to understand how changing climate conditions affect bee behavior, swarming, migration patterns, and population dynamics. This information helps develop conservation strategies for bees ina changing environment.

The World Bee Project is the first independent initiative in the world to use A.I. and other advanced technologies to monitor the decline in pollinators and biodiversity from a global perspective to seek dynamic long-term solutions to benefit both nature and humankind. The main objectives of the World Bee Project are:

i) This project monitors the health and behavior of bees by understanding the factors involved in the decline of the bee population and developing conservation strategies to mitigate the issues by utilizing innovative technologies like artificial intelligence (A.I.), the Internet of Things (IoT), and big data analytics (Oracle).

ii) The World BeeProject creates a comprehensive database of pollinators and their distribution with the implementation of a new technology called smart hives, which provide real-time data regarding bee hive conditions, which helps beekeepers manage their colonies more effectively during adverse climatic conditions and take timely colony interventions.

Machine learning and artificial intelligence are revolutionary tools in bee conservation that help monitor, analyze, and intervene in bee colonies. These technologies enhance the ability to understand and protect the bee populations to support biodiversity and agriculture.

e) Growing flower strips in the agricultural landscapes

Flower strips are man-made patches to increase the diversity of flowering plants and insects in the borders and edges of agricultural patches. Flower strips are a multifunctional agronomic tool because they prevent the decline of species diversity and increase ecosystem services like pollination and natural pest control (Kowalska et al., 2022). These flower strips help in the conservation of bees, butterflies and flies. Flower strips were reported to increase the abundance of wild solitary bees and the activity of honeybees (Sydenham et al., 2023; Bommarco et al., 2021). Rundlof et al. (2018) reported a greater abundance of bumble bees (60%), honeybees (40%), and solitary bees in clover with flower strips compared to the control plot without flower strips. The species richness of bumble bees was 16% higher in clover with flower strips compared to the control plot without flower strips. Annual flower strips in agricultural landscapes benefit the bumble bee colonies by enhancing foraging success and colony growth, boosting sexual reproduction (Klatt et al., 2020), and increasing queen abundance (Bommarco et al., 2021). Flower strips with a large mixture of perennial and wildflowers increase the species richness and abundance of bees, resulting

in an ecological enhancement of the area (Buhk et al., 2018). The addition of flower strips along the borders of red clover was reported to increase the abundance and foraging activity of bumble bees and honeybees (Rundolf et al., 2018)

Government initiatives in the conservation of pollinators

In 2018, the European Commission (EC) implemented a first-ever European Union initiative on wild pollinators. Europe faces a massive decline in wild bee species under the threatened category, leading the European Union (EU) and member states to set out strategic objectives and actions to address the decline of pollinators.

The European Commission supported bee and pollinator projects through the Horizon 2020 and Horizon Europe funding programs with some objectives to conserve bees and pollinators.

1. Nourishing PRObiotics to Bees to Mitigate Stressors (NO-PROBLeMS): This objective aims to protect the bees from gut parasites like *Nosema ceranae* by developing some eco-friendly practices. Microbial and plant-based products were developed in this program to inhibit the gut parasites of honeybees.

2. Artificial intelligence to save the colonies: The EU developed a Beehome platform in partnership with an Israeli company called Beewise, a modular commercial AI-powered beehive comprised of fully automated hardware and software conserving social and solitary bees.

3. Assessment, monitoring, and mitigation of stressors on the health of bees: The PoshBee project is a consortium of academics, governmental organizations, industry, and N.G.O.s that operates to address the issue of agrochemicals to assure the sustainable health of bees and their pollination services. This project intends to deliver practice and policy-relevant research outputs to local, national, and global stakeholders in sustainable beekeeping and conservation.

4. Giving beekeeping guidance by computational-assisted decision making: The B-GOOD project mainly focused on assessing the socio-economics of healthy and sustainable beekeeping. This project aims to test and implement a common index for measuring and reporting honey bee health status (= Health Status Index, H.S.I.), which helps assess risks like pests and diseases and evaluate the effects of management practices.

I.U.C.N. develops three action plans for threatened pollinator groups in Europe, i.e.,

The first action plan is "Canarian Islands endemic pollinators of the Laurel Forest zone – Conservation plan 2023-2028" It mainly focuses on the conservation of four important insect species – two butterflies (Canary Islands large white, *Pieris cheiranthi*, The canary brimstone, *Gonepteryx cleobule*), one bee (Canarian laurisilva bee, *Lasioglossum chalcode*), and one hoverfly (Laurisilva hoverfly, *Heringia adpropinquans*) – cohabiting in the ancient Laurel forest.

The second action plan is "Teasel-plant specialized bees in Europe – Conservation action plan 2023 – 2030". This plan mainly highlights the challenges faced by wild bees specializing in teasel plants and to develop conservation strategies to save the six species. The reduction in host plants, due to agricultural intensification and the decrease in xerothermic grassland, leads to the disappearance of the six species, i.e., Dark pantaloon bee (*Dasypoda braccata*), Spiny pantaloon bee (*Dasypoda spinigera*), Swollen pantaloon bee (*Dasypoda suripes*), Silvery pantaloon bee (*Dasypoda argentata*), Large scabious mining bee (*Andrena hattorfiana*), Scabious resin bee (*Trachusa interrupta*).

The final action plan is dedicated to conservation of six hoverfly species, i.e., Orange-horned wasp fly (*Sphiximorph apetronillae*), Red-legged leafwalker (*Chalcosyrphus pannonicus*), Royal wasp fly (*Primocerioides regale*), Golden-forest fly (*Brachypalpus chrysites*), Jacobson's leafwalker (*Chalcosyrphus jacobsoni*), Black-legged leafwalker (*Chalcosyrphus nigripes*) specialized as saproxylic insects, vital pollinators, nutrient recyclers, pest predators, and indicators of ecosystem health. "Hoverflies specialized to veteran trees in Europe – Conservation Action Plan 2023 – 2030" emphasizes the significance of forestry practices that consider the needs of pollinator species dependent on dead wood and ancient trees.

● U.S. Pollinator Partnership Action Plan (P.P.A.P.)

The U.S. pollinator partnership action plan (P.P.A.P.) is a strategic initiative that aims to create a sustainable environment for pollinators and to address the factors for critical threats in declining pollinator populations, enhancing habitats and fostering collaboration with multiple federal agencies and stakeholders to promote the health and sustainability of honey bees, native bees, and other pollinators to achieve long-term success in pollinator conservation in united states.

● Canadian Bee Health Roundtable

The Canadian Bee Health Roundtable (CBHR) collaborates with a diverse group of stakeholders: representatives from the government, the beekeeping industry, agricultural sectors, researchers, and non-governmental organizations. CBHR mainly aimed to address the issues related to bee health and the sustainability of bee populations in Canada. The primary focus of CBHR is to improve bee health through research, government policies, and best practices in beekeeping and agriculture.

Conclusion

Pollinators are vital for the systematic functioning of ecosystems and play a pivotal role in the food chain. Conservation of pollinators needs policy reforms, community

participation, and adequate awareness of the appropriate conservational practices. Developing a policy framework to distribute the crop varieties along with the 'pollinator seed mixture' will create awareness amongst the farmers and the common public along the lines of conservation of pollinators. The development of habitat conservation aspects for pollinators in places like parks, schools, and museums will educate the general public about the importance of bees in ecosystem services. Organizing 'Open Day' or 'Pollinator week' will educate the common public about the buzzing bees in the natural ecosystem and their relentless service provided for the stability and benefit of ecosystems. Adopting a holistic approach of providing nesting habitats and forage resources and avoiding plant protection chemicals during crops' anthesis will help conserve these buzzing guardians.

Author's Contributions

VHS: Conceptualization, writing-original manuscript.
AU: Conceptualization, writing-original manuscript.
ANS: Writing-review & editing.
TMS: Writing-review & editing.

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