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Short Perspective

Bees, Butterflies, and Beyond the Diverse Pollinators, an Essence for the Reproductive Success of Flowering Plants

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Abstract

Pollinators are very critical when it comes to the reproductive success of plants. They promote outbreeding which holds immense significance in the era of global climate change. It allows the plants to become fertilized, to produce seeds, fruits, and eventually new plants. They are instrumental in the sustainability of our ecosystem. Thus, there is an essential need to study these pollinators to understand how, during the course of evolution, they have co-evolved with the flowering plants to shape floral architecture and community dynamics thriving in the vicinity. In this mini-view, we shall focus our discussion on some of the animal pollinators, the dwindling diversity of animal pollinators, and various associated pollination syndromes.

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Introduction

Plants are immobile; they cannot move to escape any undesirable conditions or roam around to find mates. Therefore, they must undergo either self-pollination or rely on other agencies for the transfer of pollen (containing male gametes within) from their anthers to the receptive stigma of the same flower or of a different flower on the same plant or to a flower on a different plant of the same species. The former is *self-pollination*, a strategy that results in inbreeding, and expression of undesirable recessive traits, and subsequent loss of vigor, vitality, and thus, genetic diversity. On the other hand, the second method is *cross-pollination*, which serves to promote out-breeding and increases genetic diversity, vigor, and vitality allowing the species to acclimatize and adapt to new and ever-changing environments. The agencies that mediate the transfer of pollen grains between compatible flowers or within flowers include wind, water, and animal pollinators (both vertebrates and invertebrates, especially insects). Animal pollinators are a diverse group of organisms including honeybees, bumblebees, ants, hoverflies, flies, wasps, butterflies, moths, mosquitoes, birds, bats, lizards, and fishes [1,2]. These are responsible for the pollination of most of the plants. They are highly efficient in the delivery and deposition of pollen grains on the receptive stigmatic surface. Animal pollinators get food and shelter from the plants, they pollinate. In this mini-view, we shall focus on some of the above-mentioned animal pollinators, various pollination syndromes, and the dwindling diversity of animal pollinators.

Plant-pollinator interaction

Plant-pollinator interactions have evolved significantly over a period of time, for coordination, refinement, and perfection. This has led to the development of pollination syndromes ensuring a specific pollinator pollinating a particular plant. The primitive plants were wind-pollinated. Wind pollination is a non-directional, less productive, and energy-consuming strategy. Thus, flowering plants underwent numerous changes in establishing progressive and cost-effective modes of pollen transfer by evolving and strengthening plant-pollinator interactions. Over a period of time, a shift from wind pollination to the more advanced and efficient mode of pollination has been observed and, it appears that a number of animal pollinators were selectively recruited by the angiosperms (flowering plants) for efficient pollen transfer [2]. This attribute has immensely contributed to the diversification of angiosperms, making them the dominant group by the end of the Cretaceous period (145 to 66 million years ago).

Pollination syndrome

Pollination requires, most of the time, a well-established Plant-pollinator relationship. Over the years, interacting partners have co-evolved and perfected this association to initiate and sustain physical fitness for effective pollination. Plants have developed traits that are designed to lure pollinators for pollination purposes, which is crucial for their reproductive success. However, this is true in the case of *specialist pollinators*, pollinating particular kinds of flowers. On the other hand, *generalist pollinators* visit different flowers and pollinate a range of plant species, thus undermining the syndrome concept [2].

In a community, plants are exposed to a variety of stress factors (both biotic and abiotic). One such factor is the declining diversity, abundance, and occurrence of pollinators and significant competition among plants for attracting efficient pollinators. This has evolutionarily resulted in plants investing much more in ways to advertise certain attributes, ensuring specific floral architecture to attract and reward the pollinators, and, thus, be pollinated. Under the selection pressures imposed by the pollinating agents, plants have evolved specialized floral traits that significantly maximize the chances of effective interaction between the plant and the pollinator. This interaction amicably turns into a mutualistic one and guarantees reward to the pollinator and pollen dispersal to the plant. Surprisingly, similar floral traits have been found in many evolutionarily unrelated taxa, pointing towards convergent pressure imposed by some pollinating agents or one specific functional pollinator group [3-5].

During evolution, flowering plants have learned to communicate with potential pollinators through special cues. These cues are essentially a set of floral traits such as size, color, and orientation of flowers; reward type, relative position of the male and the female sex organs and the scent produced. All such traits are eloquently displayed and advertised by the flowering plants to attract pollinators for pollination [6]. Thus, pollination syndrome is essentially a specific plant-pollinator interaction where plants have evolved in relation to the pollinators present in the landscape, ensuring a specific pollinator pollinating a particular plant [7]. This relationship is based on the premise of offering rewards to attract potential pollinators. Together, the scent, the flower color, the reward, as well as the floral structure, serve as attraction tactics to attract a specific pollinator, giving rise to a particular pollination syndrome.

Pollinators usually visit flowers for food in the form of nectar (sugar), pollen (protein), vitamins, oils, and resins that they need to feed their larva. However, they also visit flowers for shelter and mating or may use them as breeding sites. Thus, healthy plant-pollinator relationships sustain the diversity of both flora and fauna [7,8].

Melittophily

Bees are the most frequent visitors of flowering plants and are probably the most important insect pollinators. They are the keystone pollinators of the tropical ecosystem, especially in the northern hemisphere. Flowers visited and pollinated by bees constitute the most common pollination syndrome known as *melittophily*. More than 25,000 bee species are known for offering pollinating services to almost ~ 88% of the total flowering plants [2]. Melittophilous plants have developed special floral traits to communicate with and attract bees for pollination. They have sweetly scented pendant, usually zygomorphic flowers with yellow, blue, and ultra-violet colors (color blind for red color) with prominent nectar guides on the petals, with loads of sugary nectar and pollen to attract bees for successful pollination. Bees travel from flower to flower, collecting nectar and oils and in this process also pick up pollen grains on their hairy hind legs. As the bees fly on to a different flower of the same species, they deposit pollen grains on the receptive stigma leading to successful pollination.

Ornithophily

Many flowering plants have utilized advertisement tactics such as the production of copious nectar and vivid floral displays ranging from blue to red, to lure birds for pollination. Bird-pollinated flowers are largely non-aromatic, long, tubular, and pendulous. Ornithophily (Bird-flower interactions) is a common phenomenon in islands, and tropical and subtropical regions of the world, where birds such as hummingbirds, sunbirds, honeyeaters, and honeycreepers [8] visit flowers for nectar, while a few birds primarily visit flowers to seek insects hiding in the inflorescence of the plants [9].

Hummingbirds and sunbirds are the most specialized bird pollinators of wildflowers on the planet Earth. They have flexible jaws and long beaks that are highly specialized for nectar feeding. They voraciously consume nectar throughout the day to obtain sufficient energy to perch/hover continuously. Plant species viz. *Bignonia sp, Strelitzia sp.*, *Fuchsia sp.*, *Ravenala sp.*, *Nectariana alfa*, and *Erythrina indica* are pollinated by birds. According to the U.S. Forest Service, there are about 2,000 species of birds, worldwide, involved in pollinating just a few food crops, including banana, papaya, nutmeg, trumpet creeper, red bee balm, and fuchsia.

Chiropterophily

Almost 530 species of flowering plants are known to be visited and pollinated by nectar-feeding bats [10]. They together constitute the chiropterophilous syndrome. Bats belonging to the families Ptropodiadae and Phyllostomidae are important pollinators in tropical and desert climates. The bat-pollinated flowers are large, tubular, cup-shaped, radially symmetrical, have dull color (in some cases white, brown, or green), pungent musty smell (due to sulfur-containing compounds), and are suspended atop tall stalks (flagelliflory), away from the foliage on tree trunks. These flowers are also characterized by nocturnal anthesis, i.e., the opening of flower buds at dusk or at night.

Bats are primarily nocturnal, color blind, and volant (i.e., able to fly) mammals; they are characterized by their elongated snout and tongue. Bat pollinators rely on echolocation to locate nectar sources. These specialized morphological trails help them to feed on nectar and pollen. While feeding on nectar, loads of pollen grains fall and stick on their elongated snout, face, and body, which is then deposited on the stigma of the compatible flower. The flowers of *Bauhinia melanandra*, *Eperua falcata*, *Oroxylum indicum*, *Kigelia pinanta,* etc. are known to be bat-pollinated.

Psychophily

Besides, occupying a vital position in the ecosystem, butterflies are known for adding aesthetic value to the environment. Despite such a vital function, flower visitation and pollination by butterflies has, thus far, received low attention and has been poorly studied [1,2]. There is a lot more to be investigated about butterflies and their association with plants. There are nearly as many butterflies as bees with around 17,500 different known species. In spite of such a huge diversity, not all the butterflies visit flowers. However, butterflies with mouthparts adapted for feeding on liquid food, visit flowers to collect nectar and pollen with the help of a long flexible proboscis. While sucking nectar, pollen grains stick to various body parts of the butterfly, such as the proboscis, the head, the wings, and the legs The adhered pollen is then deposited on the receptive stigma when the butterfly moves on to another conspecific flower for pollination. This pollination is sometimes also called Psychophily. Butterfly pollinated flowers are conspicuous and brightly colored, usually yellow but may also be orange, red, or blue. They are scented and usually open in the morning. Madagascar periwinkle, Lantana, and phlox blooms are just three examples of the many flowers uniquely '*designed*' for butterfly pollination.

Phalaenophily

Pollination carried out by moths at dusk is known as phalaenophily. Moths are pollinators to a significant number of flowering plants throughout the world and in the Himalayan ecosystem as well (Zoological Survey of India). Over the years, moths have adapted for nighttime pollination. Moth-pollinated flowers are usually large, fragrant, white, or pale and radially symmetrical with tubular/funnel-shaped corolla. Some classic moth flowers are angel's trumpet, moonflower, and woodland tobacco.

Cantherophily

Beetle is among the first flower-visiting insects to establish pollen-based interactions with plants. They are considered essential pollinators of a section of flowering plants that were first to evolve such as magnolias and spicebush. They were, thus, instrumental in the reproductive success and diversification of early flowering plants. Further, beetle-pollinated flowers are unspecialized usually large, bowl-shaped, dull, or off-white in color, emitting characteristic rotten or fermented odor from their pollen grains. This odor plays a significant role in attracting beetle pollinators. Pollen grains stick onto the hairy legs of beetles and are transferred to the stigmatic surface of conspecific flowers [10].

The less common pollination syndromes, such as myophily, myrmecophily, and malacaophily, i.e., pollination by flies, ants, slugs, and snails, respectively, have also been reported. However, their impact i.e. the extent to which these organisms help in pollination has been negligible, although malacophily has been reported in *Chrysanthemum leucanthemum* and *Aspindistra lurida.* In these plants, the flowers with flat stigma open at the soil level, and, this condition is best suited for malacophily [10].

Impact of pesticides on pollinators

Insects have been known, for a very long time, to be good for us all; they have been shown to be very beneficial to us in many ways. Insects, being the most diverse and dominant group of organisms, play a variety of functional roles that are critical for sustaining the cybernetics of our global ecosystem. They are known for their pollination potential across the world. About 88% of the flowering plants (angiosperms) are essentially entomophilous and are pollinated by insects [2,4]. The world population is increasing at an alarming rate and, as per the report, the '*world's population prospects*' is approximately around 7.94 billion. In order to meet the global food demands, the use of intensive agricultural practices, chemical fertilizers, and pesticides has become a routine, and a new normal is to produce more and more food. Pesticides such as imidacloprid, pyrethroid, cyhalothrin, thiamethoxam, clothianidin, indoxacarb, etc. exert a negative impact on pollinators (Table 1); this has significantly weakened Plant-pollinator interactions. A decline in diversity, abundance, and occurrence of pollinators (especially honeybees), has been reported from various corners of the world [7,11].

Effect of pesticides on honey bees

The most significant group among the insect pollinators is honey bees. Honey bees are responsible for pollinating ~ 87.5% of the angiosperms, which contribute more than 35% of the estimated global food production [1]. However, indiscriminate use of pesticides has significantly brought their number down at the local, regional global levels [12]. A decrease in population of wild bees, honeybees and bumble bees has been reported and documented in South America [11], Asia [12], South Africa [13], Britain & Continental Europe [14,15], and North America [16].

In recent years, besides the bee species, the population of pollinating insects, such as hoverflies, flower-visiting wasps,

Table 1: Pesticides and their effects on insect pollinators.

Pesticide	Effect	Citation
Imidacloprid and Pyrethroid Cyhalothrin	Combined exposures of pesticides viz. Imidacloprid, pyrethroid, and Cyhalothrin pesticides cause chronic adverse effects on honeybees including impairment of physiology function, disruption of foraging, olfactory, learning, and memory performance, increased worker bee mortality, and increased likelihood of colony collapse.	Liu, et al. 2022 [47]; Gill, et al. 2012 [48]
Thiamethoxam	Nonlethal exposure of thiamethoxam to honey bees was found to cause high levels of mortality due to homing failure, putting colonies at risk of collapse.	Henry, et al. 2012 [49]
Clothianidin and Thiamethoxam	Clothianidin and Thiamethoxam affect the foraging behavior and antennal sensitivity in bees and are hence probably detrimental to pollination and the reproductive success of bees. Together with Thiamethoxam, the pesticide causes reduced feeding and locomotor activity in bees, and bumble bees, and impaired decision-making in honey bees, thus having the potential to endanger vital ecological services.	Krupke, et al. 2012 [50]; Straub, et al. 2021 [23]
Imidacloprid	Results in cognitive impairments i.e. impairments in olfactory learning, visual learning, and memory. Such impairments affect the ability to encode/decode the memories of resources, thus affecting the process of collecting hive resources.	
Imidacloprid	It works by affecting the nicotinic acetylcholine receptor in insect pollinators and interferes with the transmission of stimuli. This leads to blockage of the nicotinergic neuronal pathway. By blocking nicotinic acetylcholine receptors, imidacloprid prevents acetylcholine from transmitting impulses between nerves, resulting in the insect's paralysis and eventual death.	Pettis, et al. 2013 [51]; Sabry, et al. 2021 [52]
indoxacarb	Indoxacarb has also a new mode of action against insect pests. It works as a sodium channel blocker resulting in paralysis and death of targeted pests.	Sabry, et al. 2021 [52]
Imidacloprid, Thiamethoxam and Chlorpyrifos	Imidacloprid, thiamethoxam, and chlorpyrifos are three of the common pesticides known for severe effects on bees and bumblebee health. They act mainly by blocking the normal conduction of the insect central nervous system by selectively controlling the nicotinic acetylcholinesterase receptors in the insect nervous system, leading to paralysis and death of the honey bees and bumble bees.	Krupke, et al. 2012 [50]; Fairbrother, et al., 2014 [46] Zhang, et al. 2022 [19]
Clothianidin and Thiamethoxam	These pesticides impair the nervous system of insect pollinators, by blocking nicotinic acetylcholine receptors, causing paralysis and death.	
Imidacloprid	Pesticides largely damage/destroy cells in the gut, brain, or other tissues via oxidative stress, thus affecting bee physiology and behavior. Pesticides have also been known to affect the reproductive potential of the bees by reducing sperm viability (in drones) which causes poor mating behavior.	
Neonicotinoids and Coumaphos	These pesticides have been found to reduce the foraging ability of bees, apart from killing the bees at higher concentrations. These pesticides could affect bee brains. Studies also indicate that bees that feed on neonicotinoid-contaminated pollen and nectar produce fewer offspring.	Rigosi, et al. 2022 [20]; Chmiel, et al. 2020 [45]; Straub, et al. 2021 [23]
Phenylpyrazoles and Neonicotinoids	Drones are also affected by pesticides viz. Phenylpyrazoles and neonicotinoids. Sublethal concentrations of these pesticides can reduce sperm viability which can hamper fertilization of queens and the production of diploid workers.	
Neonicotinoids	Neonicotinoids have a detrimental influence on bee decline. It affects the bee's nervous system, and impairs their communicating ability, precisely by disrupting bees' navigational memory and ultimately results in disorientation, reduced foraging ability, and brooding behavior.	Saleem et al., 2023 [24]
Paraquat	Paraquat has the potential to interfere with metabolic and reproductive processes in pollinators, especially honey bees. It negatively influences brood development and impairs honey bee larval development.	Sponsler et al., 2019 [53]

butterflies, and moths, has been on the decline. Studies carried out in different parts of the world have arrived at a common conclusion that both the presence of healthy pollinators and healthy plant-pollinator interactions are imperative for meeting increasing global food demands. However, the unfortunate reality is that many of the insect pollinators are experiencing a decline in numbers. For example, domestic honeybee stocks are declining at alarming speed throughout the world. About 59% of the decline has been reported from the USA in a span of five decades. The scenario in Europe is also poor, in a span of less than two decades, a decline of more than 25% has been documented [17].

Pollination is crucial for fertilization, fruit formation, and subsequent seed sets. The decrease in the diversity, abundance, and occurrence of the pollinators would mean a decreased seed set, and lowered crop production; this threatens global food security. Thus, loss of diversity due to anthropogenic interference invites a humanitarian crisis across the world that further aggravates during the pandemic as was witnessed amidst COVID-19.

Not all plants bear the equal brunt of biodiversity loss. Flowering plants, which share a special interaction with a particular pollinator (specialist pollinator), suffer the most. Such flowering plants are more vulnerable to decline, and many have declined in parallel with their pollinators [18].

How do pesticides affect

Insect pollinators are intentionally or otherwise exposed to lethal or sublethal doses of a cocktail of pesticides via multiple routes (air, water, soil, plants, or plant products). The majority of pesticides function as neurotoxins, specifically targeting nicotinic acetylcholine receptors, which can cause paralysis and spasms that ultimately result in death [19], besides impairing the cognitive behavior of insects, affecting the learning and memory of both wild and managed bees. Impaired cognitive behavior of foraging bees would critically undermine their ability to locate nectar and pollen sources [20].

Non-target insects make up the majority of insect pollinators. They live and/or visit the same areas as unwanted insect pests. Thus, they are unintentionally exposed to low-concentration, sublethal doses of pesticides which can have negative impacts both at an individual and colony levels, ranging from cognitive impairments i.e. impairments in olfactory learning, visual learning, and memory performance. Such impairments affect the ability to encode/decode the memories of resources, thus affecting the process of collecting hive resources. This also leads to increased brood and worker bee mortality and increases the likelihood of colony collapse [19-22], a condition that has been commonly termed Colony Collapse Disorder (CCD). The type and extent of these effects further vary with exposure level, duration, and route.

Recent studies have highlighted significant concerns regarding the impact of pesticides on pollinators, particularly bees. Pollinators, essential for the reproductive success of many crops and wild plants, face numerous challenges from pesticide exposure. Pesticides can harm pollinators directly by causing lethal or sub-lethal effects. Lethal doses can kill bees outrightly by interfering with the functioning central nervous system of insects, leading to paralysis and death [23] while sub-lethal doses can impair foraging, learning, and difficulty in navigating back to their hives and immune responses, ultimately affecting their survival [24]. Scientific investigations using microcolony models of bumblebees indicate significant negative impacts on colony growth and reproduction even at environmentally relevant concentrations [25].

Honey bees are often exposed to multiple pesticides, leading to potential synergistic effects that can exacerbate toxicity. By using a multi-residue pesticide analysis method, it has been reported that one and thirteen different pesticides had featured between in the analyzed pollen samples, with some samples containing up to 29 pesticides [25]

A brief account of the effects exerted by a range of pesticides at cellular, sub-cellular, and molecular levels is described below;

A high-resolution respirometry technique was used to investigate how extended sublethal exposure to imidacloprid considerably increases the oxygen consumption in the flight muscles of bumblebees. They proposed that a sudden increase in oxygen consumption resulted in decreased flight duration and flight activity. This demonstrates how pesticides based on neonicotinoids have a detrimental influence on energy production and respiration [26].

Radiofrequency tracking technology and gene expression analysis were used to understand the molecular aspects of pesticide effect on foraging behavior and reproduction. They found that homing flight time and the expression of a gene associated with oxidative phosphorylation were correlated in bees that were repeatedly exposed to neonicotinoids. They proposed that a disturbance in energy metabolic processes could be one of the causes of extended homing flights [27].

By using gas-chromatography-coupled electroantennography, the effects of two neonicotinoid pesticides on honey bees' olfactory perception of floral and pheromonal odor compounds were investigated. In order to differentiate between short-term and long-term effects, they exposed bees to neonicotinoid exposure the following spring. Antennal responses to particular floral chemicals, queen mandibular pheromone, and alarm pheromone components were altered by thiacloprid treatment. Treatment effects were generally more prominent in the short term, suggesting that the adverse effects of neonicotinoid exposure may not persist across generations [28]. Further, it was discovered that honey bee optomotor behavior is altered as a result of long-term exposure to sulfoxaflor or imidacloprid, either alone or in combination. This behavioral effect is linked to elevated stress and altered detoxification gene expression in the brain. Neuronal apoptosis in the optic lobes was elevated in response to sulfoxaflor but not imidacloprid. They imply a dysfunction of the wide-field visual motion neural circuit that drives optomotor actions [29].

Diversity of pollinators

It is extremely difficult to have an estimate of the diversity of life forms on our planet Earth. However, it is generally argued that the total life forms present on the earth range between 1 to 10 million, encompassing a huge diversity of arthropods, mostly insects. Undoubtedly, insects are the largest group of pollinators pollinating more than 80% of the flowering plants which contribute approximately 34% of global food production [1]. The estimated number of pollinator insect species is more than 349,368. They are known to be of use to approximately 352, 000 species of angiosperms, and some gymnosperms, such as *Ephedra*, *Gnetum,* and *Welvetschia* [30,31]. Among the insects, the most dominant group of pollinators is Lepidoptera with more than 1,40,000 species (particularly moths and butterflies). They are expected to visit flowers; accidentally, or otherwise, they would initiate fascinating plant-pollinator relationships. In numbers, Lepidoptera is followed by Coleoptera (7,73,00 species), Hymenoptera (70,000), and Diptera (55,000). Diptera is the least diverse group of all the groups [2,32].

Besides insects, there are some vertebrate groups that are effective pollinators, pollinating a sizable population of flowering plants. However, these vertebrate groups are significantly low in number and diversity; they include birds, bats, rodents (in the tropics), and lizards (oceanic islands). There is no data to suggest that pollination in seagrass is accomplished by a fish species [2,33,34]. We note that not all pollinators are equally efficient; their efficiency and effectiveness vary significantly and can be attributed to three different yet interrelated components; (i) abundance of pollinating species in the region; (ii) floral constancy of a pollinator to visit a particular flower; and (iii) collection and deposition of pollen onto the receptive stigma of a conspecific flowers.

Distribution pattern of pollinators

It has been observed that the pollinating organisms increase manifold with latitude and accordingly tropics have more pollinators. The increased richness of pollinators in the tropics corresponds and correlates with the increased floral diversity [2]. However, this is not always true. It is an established fact that among the insects, bees are the dominant pollinators; their diversity is highest in the dry subtropical and Mediterranean type of climate [35,36].

In one study, Pauw A. 2007 showed that the network of plants and their pollinators is less specialized in the tropics. This is true in the context of the Northern Hemisphere. But, in the southern hemisphere, the trend of increased specialization towards the tropics has been observed [37] and attributed to the geo-climatic stability of the southern hemisphere which has allowed specialized niches to persist.

Loss of pollinator diversity

Since we have clearly ongoing climate change, it is imperative to understand the decline in pollinator occurrence, diversity, and abundance at all levels: local, regional, and global. The decline in pollinator occurrence, as well as in diversity and abundance, has a direct impact on agricultural productivity and ecosystem functioning [38]. Decreased agricultural production indeed poses a serious threat to food security and may result in a global food crisis.

Through various investigations, evidence has been put forth to substantiate the fact that there is an obvious decline in pollinator diversity, occurrence, and abundance both in time and space [39]. A significant decline in the diversity and abundance of wild bees, bumblebees, honeybees, hoverflies, butterflies, beetles, moths, ants, flowering wasps, bats, birds, and even mammals, has been documented in all the continents (except Antarctica which does not have them) at the global level [40]. Besides climate change, land use changes, rapid urbanization, intensification of agriculture, industrialization, use of pesticides, pollution, and the presence of exotic species and pathogens are responsible for the unprecedented decline of pollinator occurrence, abundance, and diversity [39,40].

It is well known that climate change has altered the ecosystem dynamics to a large extent. The summers are getting hotter and the winters harsher. This has brought drastic changes in the life of flowering plants. The flowering season becomes shorter and the plants tend to flower earlier which leads to asynchrony with the pollinators, resulting in less seed set and reduced reproductive fitness [2,38].

Introduction of pollinators: A concern

To increase the chances and efficiency of pollination, subsequent fruit formation, and seed set, several pollinating insects, particularly bees have been introduced to enhance pollination rate [30,41]. Increased pollination rates are directly related to increased crop yield. However, the introduced non-native pollinators can out-compete the native pollinators [41]. The precise ecological impact of such an introduction has not yet been evaluated in detail. Impacts can range from negative to positive depending upon the introduced species, the purpose of the introduction, and the local density of the pollinator [41]. One of the bee species, Western honeybee (*Apis mellifera*), has been indiscriminately introduced in many parts of the world for pollination purposes to increase crop production to meet global food demands [17]. A number of studies have confirmed that the western honey bee successfully becomes integrated and established in the local pollination web and at the same time, it does not exert any adverse impact on the native pollinators [42]. However, its behavior in nature needs to be studied in detail.

Similarly, *Bombus terrestris* has also been introduced in many parts of the world. It has started exerting a negative impact on native pollinators and is thus widely considered an invasive *alien* in a non-native region [43]. The *Bombus terrestris* has been associated with the loss of native Bombus species [11]. We believe that the threats inflicted by the introduced pollinators may range from fierce competition to pathogens/parasites to an array of diseases that the introduced species can bring and 'communicate' with the native species.

Future perspectives towards the protection of pollinators

i. Pesticides pose a multifaceted threat to pollinators through direct toxicity, sub-lethal effects, and the introduction of pathogens. The synergistic effects of multiple pesticide residues further complicate the issue. Efforts to protect pollinators encompass a variety of strategies that address their habitat needs, reduce harmful exposures, and support their overall health which includeDeveloping and promoting bee-friendly and effective farming systems such as promotion and incentivization of organic farming in agricultural landscapes. This is expected to increase the abundance and diversity of pollinators which in turn would favor an increase in ecosystemic services, such as pollination, and increased productivity of insect-pollinated field crops, a step towards sustainable agriculture [44,45].

ii. Restoring and improving nutritional resources for pollinators is crucial for their health and survival. Pollinators, such as bees, butterflies, and other insects, rely on diverse and abundant floral resources for nectar and pollen, which provide essential nutrients. This can be achieved by planting diverse native flora, restoring habitats, reducing pesticide use, enhancing agricultural landscapes, supporting pollinator health, and promoting conservation practices. These strategies ensure that pollinators have access to abundant and high-quality food sources, thereby supporting their populations and the essential ecosystem services they provide. Collaboration among farmers, land managers, gardeners, policymakers, and the public is vital to successfully implement these initiatives and create a thriving environment for pollinators [44].

iii. Habitat enhancement and restoration e.g. introduction of extensive grasslands and flower strips has been shown to have overall positive effects on wild bee abundance and richness. Habitat restoration and protection of natural and semi-natural habitats, which naturally promote bee abundance and richness might represent more efficient and reliable alternatives for promoting resource diversity and sustainability, and ultimately improve bee health [45-47].

iv. Implementing best management practices to reduce exposure, and ongoing research to understand and mitigate the impacts of pesticide interactions. By implementing these strategies, the health and survival of vital pollinator populations can be ensured.

Conclusion

Pollinators play a vital role in regulating the ecosystem which supports directly or indirectly two-thirds of the world's population in fulfilling their food requirement. Due to anthropogenic activities, the behavior of pollinators is affected. Exposure to lethal and sub-lethal levels of pesticides is harmful to pollinators in many ways viz. abnormal foraging activities, impaired brood development, and neurological or cognitive effects that result in the decline of the pollinator population worldwide. Without animal pollinators, mankind and the Earth's entire terrestrial ecosystem would collapse. Thus, there is an immediate need to conserve pollinators at all levels and immediate attention to sustainable alternatives like organic farming Integrated pest management practices, conserving and establishing habitats that support health and resilience, and regulatory measures need to be given to protect these essential contributors to biodiversity and agriculture.

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