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Review Article

INSECT POLLINATION: AN INCREDIBLE NATURAL SERVICE FOR FOOD SUSTAINABILITY IN AGROECOSYSTEMS-A REVIEW

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ABSTRACT

Insect pollination plays a pivotal role in the reproductive success of many flowering plants, essential for maintaining biodiversity and ensuring food security in agroecosystems. While plants rely on various pollinators, insects are the primary contributors to this natural service, transferring pollen as they forage for nectar and pollen rewards. This mutualistic interaction between plants and pollinators is crucial for the sustainability of both natural and agricultural ecosystems. However, the increasing threat to pollinators from habitat loss, pesticide use, and climate change jeopardizes this vital ecosystem service. The decline in pollinator populations is particularly concerning for global food security, as many crops depend on insect-mediated pollination. This review examines the mechanisms of insect pollination, the factors contributing to pollinator decline, and strategies to enhance pollinator populations. Emphasis is placed on the importance of conserving native pollinators, optimizing agricultural practices, and mitigating environmental stressors to sustain pollination services for future generations.

Keywords: Beekeeping, Flowering plants, Honey Bee, Mutualism, Productivity

Entomophilous pollination, a key area of study in entomology, is an essential ecological mechanism that underpins the reproduction of over 80% of the world's flowering plants (Tanda, 2022a, b; 2023a-c). This process is crucial for the survival of both human societies and terrestrial ecosystems globally. However, the diversity of pollinators within agricultural systems is increasingly threatened by the widespread adoption of intensive farming practices. Such practices disrupt natural habitats and pollinator populations, ultimately compromising the effectiveness of pollination services that are vital for food production and ecosystem health. Many crop species rely on a diverse range of animals, particularly insects, for the transfer of pollen. These insect pollinators are vital to the reproductive success of crops. Plants attract pollinators by emitting distinctive scents and visual cues, guiding them toward the flowers to facilitate pollen transfer. This intricate interaction between plants and pollinators ensures the continuity of crop production and biodiversity.

Floral entomophily has fostered strong, mutually beneficial relationships between flowering plants and their pollinating animals. Modern agricultural industries around the world heavily rely on insect pollination services to ensure crop productivity. Notable pollinators, such as honey bees, native wild bees, and various species of flies, contribute significantly to global food production. These pollinators provide ecosystem services valued at billions of dollars annually, with estimates ranging from $235 to $577 billion USD per pollination season, highlighting their critical role in the global economy (FAO, 2018; Tanda, 2019a, 2020a, 2021a-d; Tanda, 2022a, b; 2023a-c).

Crop-insect pollinators

Bees, beetles, flies, wasps, thrips, butterflies, and moths are all highly effective pollinators. Their ability to fly enables them to cover large distances quickly, making them efficient at transferring pollen to the stigmas of multiple flowering plants during a single foraging session. This rapid and widespread pollen transfer enhances the pollination process, supporting the reproduction of a diverse range of plant species, including important crop plants.

Entpollinatology – Exploring the science of insect pollination

Entpollinatology combines the Greek word ἔντομον (entomon), meaning 'insect', with 'pollination' and '-λογία' (-logia), meaning 'study of' (Tanda, 2022a,b; 2023a-e). This emerging field is dedicated to the scientific study, management, and utilization of insect pollinators, representing a specialized branch of zoology. The term *Pollinatechnology* refers to the techniques or methods used to transfer pollen from the anther of a flower to its stigma. Entpollinatology, as a newly proposed scientific discipline, focuses on understanding and harnessing the role of insects in the critical process of pollination, which is vital for the fruit production of many crop plants

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(Tanda, 2019a, 2020a-c, 2021a; Tanda, 2022a, b; 2023a-c).

Numerous crops, both agricultural and wild, rely heavily on pollination services provided by honeybees, due to the efficiency and consistency they offer within modern agro-industrial systems (Aizen *et al*., 2008). Among insects, honeybees are arguably the most beneficial to global food production. While staple crops such as wheat, corn, and rice, which do not require insect pollination, account for roughly 65% of global food production, approximately 35% of crop yields depend on pollinators for seed and fruit production. This includes not only crops but also livestock production, as pollinator-dependent fodder is crucial for animal husbandry (Dias *et al.*, 1999).

Pollination is a vital ecosystem service that extends beyond agricultural systems, with wild plants, crops, and even livestock feed all relying on a diverse group of pollinators. Insects, particularly bees, are the primary pollinators, although birds, bats, and other animals also contribute. Wild solitary and social bees play a significant role in pollinating both managed crops and natural ecosystems, enhancing biodiversity and productivity across various environments. Economic crops such as apples, citrus fruits, tomatoes, melons, strawberries, apricots, peaches, cherries, mangoes, grapes, olives, carrots, potatoes, onions, pumpkins, beans, cucumbers, sunflowers, various nuts, herbs, cotton, alfalfa, and lavender are all dependent on insect pollination services, particularly those provided by bees (Tanda, 2019b, 2020a; 2021a-d).

While the honeybee (*Apis mellifera*) is the leading insect pollinator worldwide, the contributions of native wild bee species must not be overlooked. Pollination systems, which are critical for food security, sustainable agriculture, and environmental management, rely on both managed and wild bee populations. Moreover, crops that produce fiber, such as cotton, and other products like timber, also require pollination for continuous production (Tanda and Goyal, 1979; Tanda, 2019b, 2020a,b, 2021a-c; Tanda, 2022a,b; 2023a-c).

Bees are essential to the pollination of many fruit and vegetable crops. In particular, crops with limited pollen availability can benefit from advanced pollination technologies, which enhance productivity without the need for costly chemical inputs. In many instances, bee pollination significantly boosts crop yields, even if growers may not always recognize its contribution, as long as the necessary environment and supplemental bee populations are present. However, large-scale monocropping and modern agricultural practices, if not carefully designed, can diminish the availability of plant pollinators. Moreover, the indiscriminate use of pesticides, while intended to control pests and diseases, can harm pollinator populations unless managed with extreme care. Thus, a balance must be struck between crop protection and the preservation of pollinator health to ensure long-term agricultural productivity.

The necessity of bee conservation

Despite the well-established role of insect pollination in food production, many farmers continue to overlook the importance of pollinator conservation. As global demand for food increases, agroecosystems and the natural habitats of pollinators are being modified to meet the needs of food security. It is crucial to identify which pollinators are most beneficial for enhancing agricultural productivity and to prioritize their conservation within our agro-environment. Pollinator species and their effectiveness vary depending on the crop and cultivar. While many crops do not rely on insect pollinators for fruit or seed production, their yields can significantly improve when cross-pollinated by insects. Some plants are self-pollinating or exclusively cross-pollinated by a specific species, while others are pollinated by a variety of insect visitors, or even by wind or water currents. The efficiency of pollination can also differ based on the location of the same plant species.

Honeybees (*Apis mellifera*), in particular, provide invaluable pollination services, with their solitary contribution to crop pollination estimated to offer over $14 billion in economic value to the agro-industry. Crops such as apples, cherries, melons, alfalfa, almonds, sunflowers, and a variety of berries are highly dependent on honeybee pollination. While only a limited number of bee species are utilized at a commercial scale for crop pollination, the strength and management of apiaries are essential for the continued success and sustainability of global agricultural production. Advanced beekeeping practices, along with effective pollinator habitat management, are crucial for maintaining the resilience and productivity of agroecosystems. Therefore, investing in bee conservation is not only a matter of protecting biodiversity but also ensuring the long-term viability of our food systems.

Insect pollinators: Indispensable for high yields and food sustainability

Insect pollinators, particularly bees, are essential for ensuring the sustainability of many micro-nutrient-rich crops, including fruits, vegetables, nuts, seeds, and oils. Without these pollinators, the production of these vital food sources would face significant challenges. Approximately 75% of the world's crops that produce fruits and seeds for human consumption rely, at least in part, on insect pollinators. This includes some of the most important food crops, essential for both human nutrition and agricultural economies. The beekeeping industry plays a critical role in sustaining pollinator populations by providing bees with protected spaces to build colonies and carry out their vital pollination work. In turn, maintaining a healthy bee population is essential for ensuring the continued productivity and quality of many food crops. Furthermore, apiculture (the practice of beekeeping) offers valuable opportunities to study bee habitats, behaviours, and ecological interactions, contributing to a deeper understanding of how best to protect and manage these crucial pollinators. Keeping in view the central role bees play in global food security, it is imperative to prioritize their conservation and ensure their habitats are preserved for the health of both ecosystems and agriculture.

Role of the U.S. Department of Agriculture (USDA) in pollinator management

The U.S. Department of Agriculture (USDA) has played a critical role in advancing our understanding of the relationship between bees and their surrounding landscapes. In 2019, the USDA introduced new methodologies and technologies to help land managers and scientists assess how the landscape impacts bee health and behaviour. These tools provide vital data for making informed decisions about where to position apiaries during the summer and fall, after crop pollination has ended. Strategically placing hives in these locations ensures that bee populations can build strong, healthy numbers in preparation for their migration to California for almond pollination.

As the most versatile commercial pollinator, honeybees not only contribute to crop pollination but also produce honey-a unique and valuable product. Despite their importance, the global decline in honeybee populations has raised significant concerns regarding their role in agroecosystems (Aizen and Harder, 2009; van Engelsdorp *et al.*, 2007). The persistent use of acaricides to control parasitic mites, such as *Varroa destructor*, and the overuse of pesticides in agricultural areas have adversely affected bee health (Desneux *et al.*, 2007; Barnett *et al.*, 2007; Karise, 2007). These factors, alongside habitat loss and fragmentation, have led to increasing risks for honeybees and other pollinators, which are essential for global food security.

The health of honeybees is under serious threat worldwide, and any decline in their populations, along with the loss of wild pollinators, poses a growing concern. Habitat destruction and the intensification of land use in agricultural environments are major contributors to this decline (Rathcke and Jules, 1993; Tscharntke *et al*., 2005; Kremen *et al.*, 2004, 2007; Steffan-Dewenter and Westphal, 2008). Honeybees face numerous threats during their life stages, including parasitic mites (*Varroa destructor*, *Acarapis woodi*, *Tropilaelaps* spp.), bacterial infections (*Paenibacillus larvae*, *Melissococcus plutonius*), fungal diseases (*Nosema* spp., *Ascosphaera apis*), viral infections, and predation by scavenger beetles, mice, and bears. While many of these threats remain poorly understood, some parasitic species are well-documented and continue to pose significant risks to bee populations.

In addition to honeybees, non-Apis bees also play an essential role in pollination. These species are particularly important for certain crops or in specialized environments, such as greenhouses. As the demand for diverse pollination services grows, there is increasing interest in developing practices and techniques that support the commercial use of wild non-Apis pollinators. By promoting the conservation and sustainable management of these valuable species, the USDA is helping ensure the continued productivity and resilience of agricultural systems worldwide.

The importance of native bees for pollination and ecosystem health

Native bees play an indispensable role as unmanaged pollinators in various ecosystems. Their most pressing need is the conservation and restoration of their habitats. Many species of native bees can nest in small habitat patches within managed environments, such as farms, urban parks, and golf courses, as well as in natural wildlands and human-dominated areas. However, these bees face numerous challenges, including the reduction of nesting sites, loss of reproductive habitats, and the increasing threat of parasites and brood diseases. To ensure effective pollination services, it is crucial to support the healthy growth of wild bee populations, as they can significantly enhance crop pollination when managed at a larger scale.

Pollination is a critical process for the successful reproduction of many plants, particularly angiosperms (flowering plants). Bees, in particular, are vital for moving male sex cells (pollen) from the male anthers to the female stigma, ensuring the setting of seeds. Several studies have shown that many plants rely heavily on bees for this process, which is fundamental for their survival and reproduction (Renner, 1988; Nabhan and Buchmann, 1997). During their visits to flowers, bees collect nectar and pollen, which adhere to the hairs on their bodies. As they move from flower to flower, they inadvertently transfer pollen from one flower's anthers to another flower's stigma, facilitating cross-pollination and genetic diversity in plant populations. This mechanism of pollination not only promotes the genetic recombination of plants, enhancing the survival of plant offspring in changing environmental conditions, but also sustains the biodiversity necessary for natural selection and adaptation. Even in self-pollinating plants, the transfer of pollen, though minimal, still supports genetic variability, contributing to the resilience of plant populations. Cross-pollination, where pollen is transferred from one plant to another, creates even greater genetic diversity and is crucial for the long-term adaptability of species.

Insects, particularly bees, are essential pollinators for many crop species, and their role in crop production cannot be overstated. While some plants depend on wind or water currents for pollination, they must produce large quantities of pollen to ensure successful fertilization. In contrast, insect-pollinated plants tend to use less pollen and expend less energy in the process, as pollinators are often rewarded with nectar, a form of energy-rich food. However, insects, including bees, may also inadvertently transfer disease pathogens from one flower to another during their foraging activities. Despite this, insect pollination remains a highly efficient means of ensuring plant fertilization compared to wind or water pollination.

The variety of flowers that exist, with their diverse colours, scents, shapes, and sizes, attracts a wide range of pollinators. These characteristics are adapted to the specific needs of their pollinators. For instance, red, odourless flowers with hidden nectar are often pollinated by hummingbirds, while blue, aromatic flowers with exposed nectar tend to attract bees (Baker, 1975). These “pollination syndromes” reflect the evolutionary adaptations of both plants and their pollinators. Since the Cretaceous period, plants and pollinators have co-evolved, with each species developing specialized traits suited to the other. This mutualistic relationship is the foundation of pollination in both natural ecosystems and agricultural systems.

For crop pollination to be efficient, it is essential to focus on the specific foraging behaviors of pollinators. Many plants exhibit unique combinations of morphological, behavioral, and physiological traits that cater to different pollinators (Faegri and van der Pijl, 1979). Understanding these interactions is key to optimizing pollination strategies and enhancing crop yields. For example, flowers with deep nectar reserves and little scent are adapted to attract hummingbirds, while flowers with concentrated nectar and pleasant aromas are more likely to be visited by bees. This specialization helps ensure that the right pollinators are attracted to the right plants, improving pollination efficiency and crop productivity.

Pollination is not only crucial for food crops but also for maintaining the biodiversity of natural ecosystems. Poor pollination leads to lower crop yields and decreased fruit quality, which is often more detrimental than the lack of agrochemicals. In natural ecosystems, the effects of inadequate pollination may be less immediately visible, but they can be just as severe, including the loss of plant species, reduced seed production, and the decline of ecosystems dependent on those plants. The consequences can ripple through the food chain, affecting herbivores that rely on fruits and seeds, leading to vegetation degradation and the eventual collapse of the ecosystem.

A diverse pollinator population is vital for both agricultural and natural ecosystems. There are over 20,000 species of bees globally, along with many other insect and vertebrate species that serve as pollinators. Crop pollinators often engage in highly specific, mutualistic relationships with particular plant species, meaning that the loss of these pollinators can have cascading effects on entire ecosystems. For example, some wild bees that pollinate herbaceous plants depend on dry wood for nesting. When these nesting sites are destroyed, plant fertility is reduced, further impacting the pollination process.

World food production and honey bees

Honey bees are indisputably the most important and economically valuable pollinators in agriculture. These highly efficient insects are capable of pollinating nearly any crop plant, providing essential services that directly contribute to both crop yields and financial returns. For example, almonds are almost entirely dependent on honey bee cross-pollination for optimal seed setting and maximum yield. Without honey bees, the production of blueberries, squash, watermelon, and numerous other fruits would face significant declines, leading to reduced supply and higher market prices. In fact, a honey bee colony is worth 100 times more to the community than to the beekeeper, emphasizing that their value extends far beyond their direct economic worth (USDA, 2018). Honey bee pollination has played a vital role in making fruits, nuts, and vegetables more accessible to consumers and is a cornerstone of modern agriculture (Tanda, 2019a, 2020a, 2021a-c; Tanda, 2022a, b).

The importance of pollination in agriculture has been recognized for centuries. Ancient Assyrian temple carvings depict winged deities facilitating pollination of date palms, underlining the ancient understanding of the role of pollinators in ensuring successful fruiting (Buchmann and Nabhan, 1996). Historical references also describe the management of stingless bee colonies in Mesoamerica, showcasing early practices of pollination and beekeeping. In Europe, the foundation of pollination ecology can be traced back to the work of scientists like Koelreuter (1761) and Sprengel (1793), who contributed significantly to the understanding of flower pollination mechanisms (Kevan and Phillips, 2001). Despite the long-established knowledge of the vital role of pollinators in crop production, there remains a common misconception that angiosperms (flowering plants) naturally achieve cross-pollination, form seeds, and produce fruits without the need for human intervention. As a result, pollination ecology has seen slower advancement, and there is still much to be discovered about the pollination processes in both natural and agricultural environments. Surprisingly, for many key global crops, even the names of important pollinator species remain unknown. This knowledge gap presents an opportunity for researchers and apiculturists to contribute to the field of pollination biology, identifying new pollinator species and exploring their roles in crop pollination. Pollination involves the transfer of pollen from the male anthers of a flower to the receptive stigma of the female part, a crucial process for seed formation and successful crop production. This mechanism is especially important in crops with separate male and female flowers, where cross-pollination is essential for setting seeds and ensuring high-quality fruit. Bee pollinators are particularly important in fruit and vegetable production, as they not only enhance the fertilization process but also contribute to genetic improvement by increasing seed set. For crops that rely on bee pollination, this process becomes even more critical when considering other agro-inputs such as pesticides, water, fertilizers, and pest management practices.

Currently, however, bee pollinators are facing significant declines due to a variety of factors, including changes in agricultural practices, habitat fragmentation, pesticide overuse, loss of nesting sites, and the spread of brood diseases and predators (Fig. 1). In the United States alone, damage to honey bee populations caused by pesticides is estimated to cost around $14.3 million annually. The serious decline in bee populations has raised alarm bells among decision-makers, though many remain poorly informed about the far-reaching ecological consequences of this crisis. The loss of pollinators not only threatens food production and

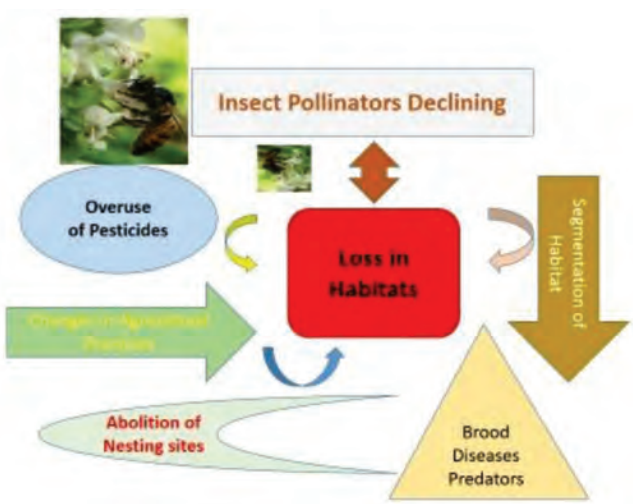

Fig. 1. Schematic representation of decline in insect pollinator populations and diversity

economic stability but also exacerbates global poverty, particularly in developing countries where agriculture plays a central role in livelihoods. Recognizing the value of bee pollinators and taking steps to protect and conserve them is not only an ethical responsibility but also a practical necessity for the future of global food security. By investing in pollinator health, we can help safeguard crop yields, promote sustainable farming practices, and support biodiversity, all of which are essential for addressing food insecurity and eradicating poverty on a global scale.

Honey bees play a crucial role in rural development, contributing to the security and sustainability of livelihoods by providing essential services in crop pollination. Their involvement enhances fruit quality and overall crop production, thus supporting agricultural economies worldwide. However, the true value of bee pollinators extends far beyond honey production, which is often overemphasized. The economic contributions of plant pollinators, particularly bees, are multiple times greater than the value of honey alone. While managed honey bee populations are highly significant, wild pollinators such as bumblebees, solitary bees, and stingless bees, also make a substantial contribution to agricultural productivity. Numerous flowering plants rely on bee pollination for successful reproduction. Bees, along with other pollinating insects, transfer pollen grains from one flower to another, facilitating the fertilization process. Pollinators come from various insect orders, including Diptera (flies), Coleoptera (beetles), Lepidoptera (butterflies), and Hymenoptera: Apoidea, to which bees belong. Among these, honey bees are considered the most effective crop pollinators due to their unique morphological adaptations, which optimize their capacity to gather pollen.

Solitary bees and sonication: A unique pollination mechanism

Sonication, or buzz pollination, is a specialized pollination mechanism in which solitary bees create vibrations to release pollen that is tightly held by the anthers of certain plants. This process is essential for plants whose pollen is not easily dislodged by simple foraging. When these bees vibrate their flight muscles while attached to a flower, the resulting vibrations cause the stamens to shake, thereby freeing the pollen. Unlike honey bees, which primarily rely on passive pollination techniques, sonication is predominantly carried out by bumblebees, carpenter bees, and stingless bees of the genus *Melipona*. This unique pollination mechanism offers new possibilities for using solitary bees in crop pollination, particularly in controlled environments like greenhouses where wild pollinators may be absent. While commercial honey bees are widely used for the pollination of a variety of crops, including those for seed production, there is growing interest in utilizing bumblebees and solitary bees for the pollination of greenhouse crops and ornamental plants. These species, with their ability to perform buzz pollination, are particularly effective in pollinating certain crops that honey bees cannot pollinate efficiently. Despite their critical role in crop production, honey bee populations are declining due to habitat loss, the expansion of monocultural farming practices, and the adverse effects of agrochemicals (Fig. 1).

Decline of honeybee and native bee populations

The decline of honeybee and native bee populations is a growing concern, driven by factors such as predators, diseases, habitat loss, and pesticide exposure. As more agricultural land becomes dependent on bee pollination, this trend is leading to an impending pollination crisis. The availability of managed bee pollinators is decreasing, while the demand for pollination services continues to rise in many countries. This imbalance is causing widespread concern regarding bee management, conservation, and agricultural sustainability (Fig. 2). Increased crop acreage, particularly in monocultural farming systems, exacerbates the pressure on bee populations by reducing the diversity of plant species and pollinator habitats. The declining number of bee pollinators threatens to undermine crop yields and food security, posing a significant challenge for global agriculture. To mitigate this crisis, it is essential to adopt advanced agricultural practices and environmental management strategies that prioritize pollinator health and habitat conservation. Sustainable farming practices, habitat restoration, and careful pesticide management can help protect both managed and wild bee populations, ensuring their continued role in crop pollination and the broader ecosystem.

Crop pollination, a vital ecosystem service, is increasingly endangered as modern agricultural practices shift from traditional methods to more technical, intensive approaches. Insecticidal sprays, which directly harm bees, and herbicides, which indirectly reduce bee populations, are among the most significant threats. These chemicals, commonly used in large-scale agricultural systems, are contributing to the decline in bee populations, which are essential for pollination. Bees play a pivotal role in the modern cropping system, not only by producing honey but primarily by enabling the pollination of a wide range of crops. In fact, it is in crop pollination, rather than honey production, that honey bees make their most substantial contribution. However, certain agricultural practices, including the widespread use of pesticides and the development of genetically modified cultivars, are considered detrimental to both bee health and beekeeping. Honey bees are among the most extensively studied insects after *Drosophila* due to their importance in pollination and their ecological role. In the United States alone, the value of crops that depend on honey bee pollination is estimated at around $24 billion annually, with commercial bee pollination services valued at approximately $10 billion each year. The demand for bee-pollinated crops is increasing, which drives the need for more honey bee colonies and efficient management practices to ensure sustainable pollination. Despite their immense value, honey bees are not always managed optimally. There is a critical need for education and awareness among growers to maximize the benefits of honey bee pollination and mitigate the challenges faced by beekeepers. The contribution of beekeeping to the agroindustry is enormous. In countries like India, honey bees are responsible for cross-pollinating over 50 million hectares of cropland, enhancing yields in oilseeds, pulses, fruits, and vegetables. Given the recurring shortages of pulses, cooking oils, and fresh produce, the importance of bee pollination is becoming increasingly evident. Bee pollination, an age-old practice rooted in mutualistic relationships between plants and pollinators, remains fundamental to the production of a wide variety of agricultural crops.

Fig. 2. Schematic representation of bee pollination crisis solution (Tanda, 2021a)

The decline in crop pollinators, particularly honeybees, coupled with the increasing demand for pollination services, presents a significant threat to global agricultural systems. This impending crisis highlights the urgent need for sustainable agricultural practices and the conservation of both wild and domesticated pollinators. Pollinators, particularly bees, have been in mutualistic relationships with plants for over 200 million years, co-evolving to create complex and innovative pollination mechanisms. These interactions, vital for seed production, are increasingly at risk due to factors such as habitat loss, pesticides, and climate change. Many crops rely on specific pollinator species to ensure successful seed setting. For instance, *Phlox* flowers are pollinated by the diurnal butterfly *Hemoris*, *Yucca* by the tineid moth *Pronuba*, and figs by the fig wasp *Blastophaga*. Red clover depends on bumblebees, while *Trollius* is pollinated by the blade fly *Chiastochaeta*. Remarkably, some female wasps of the genus *Scolia* mimic the flowers of orchids like *Ophrys insectifera*, resulting in "accidental" pollination when male wasps are attracted to the flower's resemblance to a female wasp, although they are not foraging for nectar or pollen. This intricate evolutionary relationship between plants and pollinators is one of the most remarkable examples of mutualism in the natural world. The value of insect-mediated crop pollination is estimated at $200 billion annually, and about 100,000 pollinator species, spanning insects, birds, and mammals, contribute to pollinating over 2,50,000 wild plant species. Insects such as bees, wasps, moths, butterflies, flies, and beetles, along with birds, fruit bats, and even lemurs and geckos, all serve as efficient crop pollinators. Hummingbirds, in particular, are prominent pollinators in many regions of the U.S.

However, the populations of both wild and domesticated pollinators are declining at an alarming rate. Habitat destruction, changes in food preferences, loss of nesting sites, pesticide use, diseases, and predators all contribute to this trend. Specific ecosystems are more vulnerable than others, particularly those with rare or specialized pollinators. For example, insecticides have been shown to harm not only bees but also other essential pollinators like butterflies and moths. At Cornell University, research observed that monarch caterpillars feeding on *Bt* corn pollen, which was blown onto milkweed plants near corn fields, experienced significant adverse effects. Pesticides also deplete nectar sources and nesting materials for bees, further exacerbating the decline in pollinator populations. In India, the indiscriminate use of chemicals and environmental pollution have caused alarming fluctuations in butterfly populations, with the abundance of approximately 1,500 species being severely affected. Deforestation, agricultural expansion, and urbanization have also contributed to the destruction of habitats for species like the Malabar Tree Nymph, Travancore Evening Brown, and the Bhutan Glory butterfly, pushing them to the brink of extinction. The loss of butterflies, essential pollinators for seed setting and fruit production, threatens not only biodiversity but also food security. As insect pollinator populations decline, crop pollination services are being jeopardized. In the Himalayan region, growers have reported a noticeable reduction in apple fruit production and quality, which they attribute to the disappearance of wild bees, butterflies, and moths during the critical flowering season. In response, some regions, such as Maoxian County in Sichuan, China, have resorted to hand-pollination techniques for apples. This highlights the growing need for awareness and education among policymakers, beekeepers, and farmers about the importance of pollinators. Increasing the populations of honeybees, stingless bees, bumblebees, and solitary bees could help mitigate the pollination crisis. In many Western countries, honeybees and solitary bees are already used to pollinate a wide range of crops. Moving forward, the focus of beekeeping should shift from traditional honey production to more sustainable pollination practices, which will be essential for the future of agriculture (Tanda, 2019a; 2020a-c; 2021a,b; Tanda, 2022a,b).

Insect pollinators and their importance in food sustainability

Pollination by insects provides essential support for the structure and functioning of vast natural ecosystems. It also enhances the ornamental, recreational, and cultural aspects of human life, highlighting its importance to communities. Given its ecological and economic significance, it is crucial to understand the reasons behind the decline in pollinator species, analyze its causes, assess potential consequences, and identify the necessary monitoring and protection measures. The most successful life forms on Earth include angiosperms, which produce seeds and fruit. Flower reproductive systems vary greatly among insect species, but two mechanisms are fundamental for sexual reproduction in all angiosperms: first, the movement of pollen from the anthers to the stigma of the flower, and second, seed setting after successful fertilization, where the sperm nuclei blend with the egg nucleus to develop a fertile embryo and seed (Fig. 3 and 4).

Many crops are self-pollinating, a process in which pollen transfers within a single plant, typically from the anthers to the receptive stigma of the same flower (Fig. 4). In contrast, the majority of flowering plants rely on cross-pollination, where pollen is transferred between flowers, often from different individuals. This vital service is predominantly provided by over 200,000 species of insect pollinators. Furthermore, more than 75% of the world's angiosperms depend on external agents, such as wind and water, for effective cross-pollination. Fossil records dating back approximately 130 million years reveal the remarkable diversity that angiosperms have displayed throughout their evolutionary history.

Inbreeding and self-fertilization: Genetic complications

In plants, reproductive structures can vary significantly. Some species possess both male and female reproductive organs within the same flower (hermaphroditic), while others may have only male (staminate) or only female (pistillate) organs. Flowers

Fig. 3. Schematic scientific representation of sexual reproduction involved in Raspberry flowers (Tanda, 2020b)

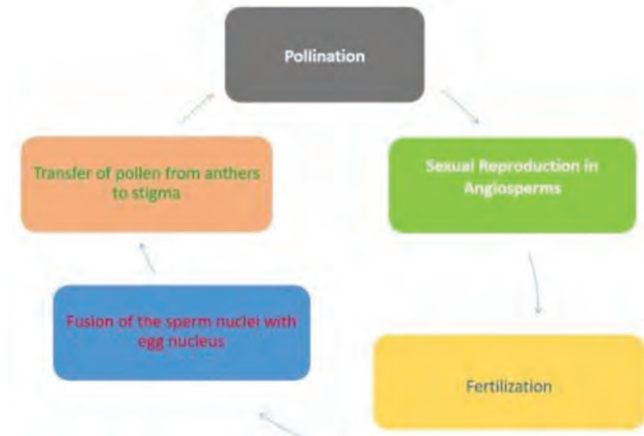

Fig. 4. Simplified representation of sexual reproduction in angiosperms

can be classified as perfect (containing both male and female parts), monoecious (having separate male and female flowers on the same plant), dioecious (with male and female flowers on different plants), or even trioecious (featuring staminate, pistillate, and perfect flowers across different individuals). Some plants exhibit unique breeding systems, such as gynodioecy, where plants bear either female or hermaphroditic flowers (Richards, 1997). Approximately three-quarters of crop species produce perfect flowers, while about 5% are dioecious and just over 5% are monoecious (Molnar, 2004). Within these species, pollination can occur both within individual flowers and between flowers on the same plant. If pollination happens within the same flower, it is termed autogamy. If it occurs between flowers on the same plant, it is known as geitonogamy. Cross-pollination between different plants is referred to as xenogamy. In many field crops, pollen from both self and outcross sources can fertilize a flower, leading to mixed genetic contributions. However, perpetual self-fertilization or inbreeding in plants can lead to significant genetic complications. As noted by Charlesworth and Charlesworth (1987), continuous self-fertilization can result in inbreeding depression, where reduced genetic variation leads to a decline in fitness. In response, many plants have evolved mechanisms to encourage cross-pollination and reduce the likelihood of selfing. These mechanisms, such as dioecy and monoecy, promote outcrossing, which generally offers a genetic advantage by increasing genetic diversity (Davies *et al.*, 2004).

The evolution of mutualistic relationships with pollinators has played a key role in facilitating cross-pollination. Insect pollinators, in particular, help broaden the genetic pool by facilitating the transfer of pollen between genetically distinct flowers. These interactions enhance the possibility of finding genetically compatible mates, thereby promoting genetic diversity in plant populations. Outcrossing is crucial for maintaining this diversity, especially in monoecious plants where self-pollination is possible. In these species, the male and female flowers often mature at different times, reducing the likelihood of self-fertilization. In hermaphroditic flowers, where both male and female organs exist within a single flower, self-pollination is often minimized by temporal separation of the maturation of male and female reproductive parts. This ensures that pollen from the male organ does not fertilize the female organ of the same flower. However, in some species, the male and female organs come into closer contact as the flower ages, increasing the potential for self-pollination before the flower is too old to produce fruit. Self-incompatibility is another mechanism that prevents self-fertilization. Many plants possess self-incompatibility systems where pollen from the same plant is rejected, ensuring that fertilization only occurs through cross-pollination. However, these mechanisms can sometimes fail, particularly due to environmental factors such as temperature or the plant's maturity, which can reduce the effectiveness of self-incompatibility (Matton *et al.*, 1994). Despite the risks associated with inbreeding, some plant species can thrive with self-pollinating or self-fertile flowers, especially in environments where cross-pollination is limited. In agricultural settings, these self-fertile plants are of great value, particularly in regions where native pollinators are absent. Their ability to self-pollinate ensures successful seed production, even in non-native environments. Richards (1997) provides a comprehensive overview of the nature and evolutionary biology of crop-breeding systems. Genetic diversity in plants can also confer resistance to pests and diseases, enhancing their ability to adapt to changing environmental conditions. For example, different levels of ovule production are seen in crops such as kiwi, tomato, watermelon, and cucumber, where multiple seeds develop from a single ovule. In contrast, crops like coconut, plum, and avocado typically produce only one seed per fruit. In some plants, insufficient pollen transfer can result in incomplete fertilization, leading to undersized or market-unacceptable fruit. Cross-pollination by multiple pollinators is often necessary to ensure that adequate pollen is transferred for successful fertilization. Without effective pollination, plants may produce small or malformed fruits, reducing their commercial value. In some cases, selective breeding and genetic engineering have been employed to overcome these limitations and ensure fruit quality (Schery, 1972). An interesting example is seedless bananas, which result from the production of triploid plants, often created through hybridization between diploid and tetraploid varieties. These plants reproduce vegetatively, bypassing the need for pollination. Similarly, parthenocarpic fruits, such as seedless tangerines, develop without fertilization, although this process is less reliable when grown in monoculture farming systems. Stenospermocarpic grapes, on the other hand, undergo fertilization but fail to produce fully developed seeds, resulting in seedless fruit (Schery, 1972).

The benefits of agricultural intensification, as Deguines *et al.* (2016) have pointed out, may be offset by a depletion of pollination services, highlighting the need for ecological intensification-an approach that optimizes ecosystem services to enhance agricultural productivity while maintaining ecological balance. Flower foragers, particularly insect pollinators, play a critical role in this process, with an estimated 4,00,000 species involved in plant-pollinator interactions. These interactions vary widely across species, with some insects serving as efficient pollinators, while others simply visit flowers for nectar or pollen without contributing to pollination.

Efficient bee pollinators, in particular, possess specialized behavioural and anatomical traits that significantly improve the precision and effectiveness of pollen transfer (Barth, 1991; Faegri and van der Pijl, 1979; Proctor *et al.*, 1996; Lewinsohn *et al.*, 2006). In this mutualistic relationship, pollinating insects receive nutritional rewards, such as nectar and pollen, while simultaneously transferring pollen from one flower to another. Some pollinators, such as certain flies, butterflies, birds, and bats, depend on pollen as a primary food source, particularly for their developing brood, which relies on protein-rich pollen (Roulston and Cane, 2000). To encourage pollination, many plants offer a variety of rewards, including nectar, pollen, resins, oils, fragrances, and other compounds (Buchmann, 1987; Barth, 1991; Roulston *et al.*, 2000; Dafni *et al.*, 2005; Roulston and Cane, 2000). The degree of interdependence between plants and pollinators varies. Some crops rely on a specific insect species or genus that has specialized pollen or nectar sources, creating a close relationship between the two. One such example is the mutualism between the yucca plant (Agavaceae) and the yucca moth (Tegeticula), a relationship that has persisted for over 40 million years (Pellmyr, 2003). Female yucca moths collect and compact large amounts of pollen, up to 10% of their body weight, using specialized tentacles. After gathering the pollen, the moth flies off to another yucca flower, where it lays its eggs, while also transferring pollen to the stigma to enable fertilization and seed setting. This intricate process illustrates a unique and highly specialized plant-pollinator mutualism, although such highly synchronized relationships are rare.

In contrast, more generalized interactions are also common. For instance, 45 insect species from five orders have been observed visiting *Geranium thunbergii* plants in a natural environment, with 11 of these species serving as key pollinators (Kandori, 2002). In the Rocky Mountains, the alpine sky pilot (*Polemonium viscosum*) is primarily pollinated by bumblebees at high altitudes and by flies at lower elevations, demonstrating how the key pollinators of a specific plant species can vary spatially or temporally (Galen *et al.*, 1987). The crucial role of insect pollination in agriculture, particularly in seed setting and fruit development, has been recognized for over 3,500 years. However, the mechanisms behind this process were not fully understood until the 17^{th} century. The idea that seeds develop from pollen deposited on the stigma was first proposed by Camerarius in 1694, but it took centuries before the significance of animal-mediated cross-pollination was widely accepted (Camerarius, 1694). The pioneering work of Carolus Linnaeus, a systematist, emphasized the importance of plant reproductive organs for classification, but it was not until the 18^{th} century that the role of animals in plant pollination became widely acknowledged, thanks to the work of scientists such as Joseph Gottlieb Kölreuter and Christian Konrad Sprengel (Kölreuter, 1761; Sprengel, 1793). Kölreuter, in particular, made significant contributions to our understanding of plant-pollinator interactions by observing insect foraging behaviour in natural environments. His studies on hybridization between closely related plant species laid the groundwork for the development of artificial pollination techniques. Kölreuter’s experiments at the University of Karlsruhe led to the first recorded cross-hybrid between two flower species, demonstrating the potential for controlled pollination in agricultural practices (Mayr, 1986; Sinnott, 1946). Despite initial resistance from the scientific community, Kölreuter’s and Sprengel’s ideas eventually influenced Charles Darwin, whose work on the “Origin of Species” (1859) revolutionized our understanding of natural selection and co-evolution. Darwin’s observations on plant-pollinator interactions, particularly in orchids, highlighted the importance of pollinator behaviour in the fertilization of plants and the subsequent effects on fruit quality. In his 1862 work, *The Various Contrivances by which British and Foreign Orchids are Fertilized by Insects*, Darwin described how pollinators contribute to plant reproduction and seed set, providing a solid foundation for agricultural practices based on pollination biology (Darwin, 1862). The work of Müller (1869), Delpino (1868-1875), Knuth (1906, 1908, 1912), and Mûller and Delpino (1869) further expanded our understanding of the adaptive mutualism between plants and pollinators.

Insect pollinator management

Prasifka *et al.* (2018) highlighted the relationship between bee foraging behaviour and specific floral traits, demonstrating how pollinator interactions can be optimized for hybrid crop production. Their work utilized genetic resources from crops like sunflower and others to identify markers associated with key floral characteristics. This approach provides a framework for leveraging nectar-related traits to enhance pollinator interactions. Future research focused on improving pollinator rewards could further increase sunflower yields by attracting more efficient pollinators, ultimately boosting crop productivity.

The domestication of bees for pollination purposes has played a pivotal role in enhancing agricultural yields and generating significant financial gains. The widespread adoption of biotic pollination techniques has led to major advancements in agricultural technology, with substantial economic impacts (Fig. 5). Among the many pollinators, the western honey bee (*Apis mellifera* L.) stands out as the most widely used domesticated species. Its remarkable efficiency as a pollinator, combined with its ability to produce honey and wax, makes it invaluable in both agricultural and apicultural sectors (Free, 1993; Kearns *et al.*, 1998; McGregor, 1976; Delaplane and Mayer, 2000). The domestication of honey bees dates back more than 6,000 years, originating in Eurasia, where they were prized for their honey and wax. This practice traces its roots to ancient Egypt, where bees were kept in hives, marking the beginning of what would become a long history of managed pollination (Dobbs, 1750; Crane, 1983, 1990, 1999). Over the millennia, the domestication and management of honey bee colonies have evolved into a sophisticated practice that has greatly contributed to modern agricultural productivity.

In the 1600s, *Apis mellifera* L. was introduced to North America by European colonists and rapidly became the key pollinator for the developing agricultural industry. Managed hives were subsequently transferred worldwide (Sheppard, 1989). In North America, modern beekeeping began in 1862 when L.L. Langstroth, a

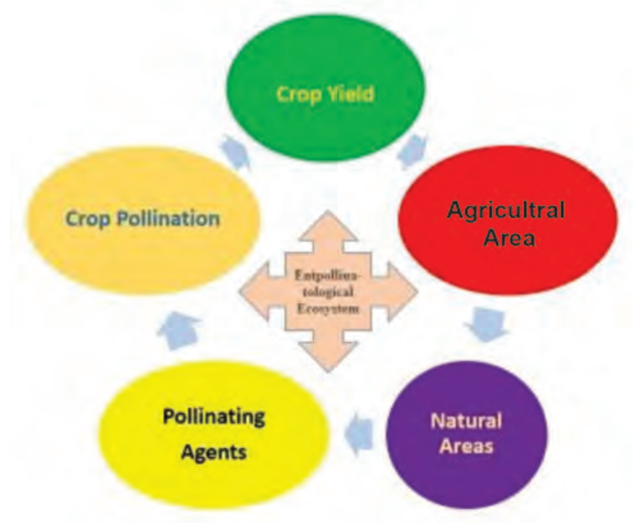

Fig. 5. Schematic representation of pollinating agents' role in crop entpollinatological ecosystem

Philadelphia minister, domesticated honey bees by utilizing the concept of "bee space" to develop portable frame hives. This innovation allowed for efficient honey extraction while preventing harm to the bee colony. Langstroth's design marked the beginning of commercial beekeeping, significantly increasing honey production and making bees a vital contributor to pollination. Today, honey bees provide pollination services for over 100 economically important crops (Free, 1993; Kearns *et al.*, 1998; McGregor, 1976; Delaplane and Mayer, 2000; Tanda, 2022a-c).

In addition to honey bees, various species of wild pollinators have been domesticated and managed for specific crop pollination needs. Bumblebees (*Bombus* spp.), for example, are predominantly used in greenhouse tomato pollination (de Ruijter, 1997; Hughes, 1996; Kevan *et al.*, 1991; Macfarlane *et al.*, 1994; Plowright, 1996; van Heemert *et al.*, 1990). Leafcutting bees (*Megachile rotundata*) are commonly used for alfalfa pollination in arid regions of the Pacific Northwest (Bohart, 1972a; Frank, 2003). For alfalfa pollination, alkali bees (*Nomia melanderi*) are also utilized (Stephen, 2003). In the eastern United States, Japanese horn-faced bees (*Osmia cornifrons*) and other mason bees are domesticated to pollinate apple orchards (Batra, 1982; Bohart, 1972b). In the northwestern U.S., *Osmia lignaria* is employed for apple pollination (Bosch *et al.*, 2000; Bosch & Kemp, 2002), and in eastern Canada, it is used for cherry fruit fertilization (Bosch and Kemp, 1999, 2000, 2001; Sheffield, 2006). Advanced methods for the reproduction and management of these species are readily available (Griffin, 1993; Torchio, 2003). Beyond honey bees, many other species of wild bees, particularly bumblebees and megachilids, are more effective pollinators for certain crops. For example, *Osmia* species are utilized for pollination in crops such as almonds (Bosch *et al.*, 2000; Bosch and Kemp, 2000; Torchio, 2003), pears (Maeta *et al.*, 1993), blueberries (MacKenzie *et al.*, 1997), sweet clovers (Richards, 2003), and blackberries and raspberries (Cane, 2005).

In addition to enhancing pollination, bees are also utilized for biocontrol in integrated pest management. For instance, bees have been employed in blueberry cultivation to distribute *Bacillus subtilis*, a biocontrol agent that controls *Monilinia vaccini-corymbosi*, the pathogen responsible for mummy berry disease (Dedej *et al.*, 2004). Similarly, in strawberry production, bees disseminate *Trichoderma harzianum* 1295-22, a biocontrol agent that suppresses *Botrytis cinerea*, a pathogenic fungus (Kovach *et al.*, 2000). Additionally, honey bees are being investigated as biological detectors for environmental monitoring. Studies have explored their potential to detect atmospheric pollutants and toxic substances (Bromenshenk *et al.*, 1995), as well as landmines (Bromenshenk *et al.*, 2003). There is also ongoing research into using honey bees to improve fruit quality and yield in crops like pomegranate (*Punica granatum*) and raspberry (*Rubus parvifolius*) (Tanda 2021a) (Fig. 6 and 7). To sustain and enhance pollinator populations, various management strategies have been developed to increase biodiversity, abundance, and overall efficiency. One key approach is modifying ecological conditions to support pollinator populations, either by enhancing their habitat or manipulating the environment to promote pollinator activity. These strategies include cultivating flowering food resources to attract pollinators, providing artificial nesting sites, and protecting natural nesting habitats (Shepherd *et al.*, 2003; Vaughn *et al.*, 2004). These passive management techniques help increase the biodiversity of pollinators, benefiting both wild and domesticated species. Targeted management strategies can focus on specific species to enhance their effectiveness as crop pollinators. By improving the habitat for species such as bumblebees and mason bees, or providing specialized nesting sites, the efficiency of pollination can be improved, ultimately increasing crop yields. These management practices are essential for ensuring the long-term sustainability of pollinator services, particularly in light of challenges such as habitat loss and climate change. To encourage the biodiversity of the crop pollinators and the populations of a special species, many new techniques are developed (Kevan *et al.*, 1990).

Fig. 6. Effect of pollination by honey bees in Pomegranate (*Punica granatum*) in improving fruit quality and yield (Tanda, 2021a)

Economic importance of insect pollinators

Agroindustry is one of the most important economic sectors globally. The yield of most crop species is significantly boosted by bee pollination services. Over 75% of the 115 leading crop species depend on, or at least benefit from, insect pollination, while only 28 crops are sufficiently pollinated by wind or self-pollination. Therefore, animal pollination accounts for an estimated 35% of global crop production (Klatt *et al.*, 2013; Tanda and Goyal, 1979). In crop production, cross-pollination plays a crucial role in both financial and bio-ecological benefits. Bee pollination provides numerous advantages to the agro-industry by contributing to the production of a wide variety of bio-products worldwide. In fruit production, for instance, the process is directly driven by bee pollination. In some cases, even though pollination does not directly result in the production of the crop itself, it still significantly contributes to improving the quality and size of produce. For example, bee pollination is essential for producing high-quality carrots and tomatoes with optimal sizes. Moreover, indirect benefits also arise through food chain interactions.

In terms of direct economic value, the alfalfa seed crop, which is pollinated by bees, has an annual value of $109 million. Additionally, hay produced for livestock forage, which also relies on bee pollination, is valued at $4.6 billion per year (Morse and Calderone, 2000). While indirect results tend to overemphasize the economic value of crop pollination, these figures have been used in numerous research programs to highlight the significant contributions of pollinators. The annual value of honey bee pollination to U.S. agriculture has

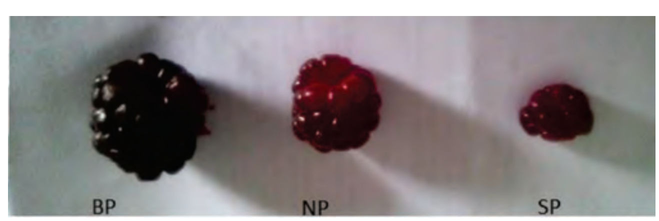

Fig. 7. Bee-pollinated fruit (BP), Naturally-pollinated fruit (NP) and not-pollinated, Self-pollinated (SP) fruits of raspberry, *Rubus parvifolius* (Tanda, 2020b)

been estimated at $18.9 billion (Levin, 1983), $1.6–5.7 billion (Southwick and Southwick, 1992), $150 million (Rucker *et al.*, 2005), $9 billion (Robinson *et al.*, 1989a, b), and $14.6 billion (Morse and Calderone, 2000). In Canada, honey bee pollination contributes $443 million annually (Scott-Dupree *et al.*, 1995). Although honey bees are indispensable, other species, such as alfalfa leafcutting bees and bumblebees, also play significant roles in crop pollination. Wild bee species, in particular, add an estimated $2 billion to $3 billion annually in pollination services (Prescott-Allen and Prescott-Allen, 1986; Southwick and Southwick, 1992; Losey and Vaughan, 2006).

In addition to insects, several vertebrate species also contribute to pollination services for economically important crops. For instance, bats are the primary pollinators for certain tree species in the Bombacaceae family, which provide valuable products such as cotton, timber, and silk (Bawa, 1990; Watson and Dallwitz, 1992). Bats and birds are also crucial for pollinating cacti and agaves, which are sources of products like tequila, mescal, and sisal fibers (Grant and Grant, 1979; Valiente-Banuet *et al.*, 1996; Arizaga and Ezcurra, 2002; Slauson, 2000, 2001; Arizaga *et al.*, 2002; Fleming *et al.*, 2001a, b; Rocha *et al.*, 2005). Overall, bee pollinators are responsible for about 30% of the production of edible oils, fibers, nutraceuticals, alcoholic beverages, and medicines derived from plants that are valuable to humans (McGregor, 1976; Roubik, 1995; Buchmann and Nabhan, 1996).

Estimating the economic significance of bees and natural pollinators in the agricultural sector is complex. The number of species involved and the lack of detailed information on species scarcity make these estimates challenging. For example, Losey and Vaughan (2006) in their study did not attempt to estimate the dollar value of plant pollination services, which remains a challenging task. However, it is practical to assume that many flowers in uncultivated terrestrial environments depend on bee pollinators for pollination, contributing to the maintenance of natural crop ecosystems.

In addition to their role in pollination, bees provide a variety of environmental services that are difficult to quantify but are nonetheless crucial. For example, bees contribute to water filtration, carbon sequestration, and the control of floods and soil erosion, all of which are essential ecosystem services that benefit cropping systems (Daily *et al.*, 1997). The ecological functions of bee pollinators extend beyond pollination to include other environmental services, although these are challenging to fully comprehend without a deeper understanding of pollination mechanisms and biological systems. Honey bees are particularly notable for their significant impact on crop pollination, with their enhanced phenotypes linked to disease resistance traits. For instance, honey bees show resistance to pathogens and pests through their enlarged phenotypes, which include honey, propolis, venom, beeswax, bee bread, and royal jelly. Each of these phenotypes has demonstrated antipathogenic properties, serving as defensive tools at the hive level to protect against diseases (Easton-Calabria *et al.*, 2019). Honey bees exhibit resistance to pathogens and pests through their enlarged phenotypes, including honey, propolis, venom, beeswax, bee bread, and royal jelly. Each of these phenotypes has demonstrated antipathogenic properties and functions as a defensive tool at the hive level to protect against diseases.

Insect pollination processes and threats

According to a UN report, Howard and Johnson (2019) highlighted that nearly one million species are now at risk of extinction. Apiculturists warn that this represents not only a crisis for biodiversity but also for humanity as a whole. The decline in bee populations, both locally and globally, poses a significant threat to flower pollinators and, by extension, to the stability of ecosystems, contributing to trophic collapse (Dobson *et al.*, 2006; Sparke, 2024). This issue was already being observed in the 1990s, with notable damage to bee hives reported in the United States (Watanabe, 1994). Buchmann and Nabhan (1996) also drew attention to the decline of both managed and non-managed pollinators, warning of the widespread devastation to biodiversity and ecological systems. They called for an urgent action plan from the U.S. government to address the declining populations of pollinators. Recognizing the critical role of insect pollination as an essential ecological service, researchers have highlighted its global importance (Daily *et al.*, 1997; Costanza *et al.*, 1997; Eardley *et al.*, 2006).

By the mid-1990s, concerns about the global decline of bee populations and its impact on biodiversity had become a focal point for scientists and agricultural experts alike (Sparkle, 2024). In 2000, at the Conference of Parties (CoP) of the Convention on Biological Diversity (CBD), policymakers established an International Initiative for the Conservation and Sustainable Use of Pollinators (the International Pollinators Initiative, or IPI). This initiative aimed to address the decline of pollinators globally and promote agricultural biodiversity. During the 5th Meeting of the CoP, the development of an Action Plan for the IPI was proposed. The plan, based on the São Paulo Declaration on Pollinators, was formally adopted at CoP 6 in 2002 (decision VI/5). This plan emphasizes the need for all stakeholders, including conservationists, farmers, landscape planners, and policymakers, to collaborate in preserving the crucial role of crop pollinators and ensuring the sustainability of biodiversity worldwide.

CONCLUSION

This review highlights the indispensable role of insect pollinators in sustaining global food production and maintaining ecosystem balance. The intricate mutualistic relationship between plants and pollinators is a cornerstone of agroecosystems, significantly influencing crop yield and biodiversity. While commercial honeybees are celebrated for their efficiency in pollination, native and wild bees, including bumblebees and solitary bees, contribute immensely to the fertilization of crops and conservation of wild ecosystems. Their "voluntary" services highlight the critical need for their protection. The management of insect pollinators is complex and requires a deep understanding of their behaviour, historical co-evolution with plants, and the ecological services they provide. Moving hives or introducing non-native bees for pollination must be approached with caution to prevent environmental disturbances. The symbolism of the relationship between humans and bees reflects a profound connection between nature and agriculture, where bees silently yet significantly support our agroecosystems.

This review not only evaluates the role of pollinators in improving the quality and quantity of agricultural produce but also highlights the need for their better utilization and ecological management. Strategies such as habitat conservation, minimizing pesticide use, and promoting sustainable agricultural practices are vital to ensure the survival and effectiveness of pollinators. Furthermore, the discussion integrates recent findings and advanced management techniques, providing valuable insights for agricultural scientists, ecologists, apiculturists, and policymakers. By bridging the gap between traditional and innovative approaches to pollinator management, this review offers a resourceful compilation for diverse stakeholders, including students, teachers, researchers, and practitioners. As pollinator populations face unprecedented challenges, the importance of their conservation and sustainable use cannot be overstated. Protecting these small but mighty contributors is essential for the long-term sustainability of food systems and the environment.

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