TRENDS IN ANIMAL AND PLANT SCIENCES
https://doi.org/10.62324/TAPS/2025.092
www.trendsaps.com; editor@trendsaps.com
E-ISSN: 3006-0559; P-ISSN: 3006-0540

REVIEW ARTICLE

Animal Pollinator Assemblages: Biodiversity Dynamics and Roles in Sustainable Agro-Ecosystems

Sumbal Shoukat*[1], Tahseen Javaid[2], Fakhar-Ur-Rasool-Arbi[3], Saima Sher Afghan[4], Fatima Tariq[5], Misbah Batool[6], Zainab Touqeer[7], and Aqsa[8]

[1,8]Department of Zoology, Government College Women University Faisalabad, [2,6,7]Department of Zoology, Wildlife and Fisheries, University of Agriculture Faisalabad, Pakistan, [3]Department of Entomology, University of Agriculture Faisalabad, [4]Department of Microbiology, University of Haripur, [5]Department of Botany, Government College Women University Faisalabad Pakistan.
***Corresponding author:** sumbalshoukat83@gmail.com

Article History: 25-052 Received: 23-Oct-2025 Revised: 23-Oct-2025 Accepted: 22-Nov-2025

ABSTRACT

Pollinators are a vital part in supporting nearly every agricultural system in the world because they provide pollination which is necessary in the reproduction of most crops that people consume. The resilience and productivity of ecosystems depend on biodiversity among the pollinators such as bees, butterflies, birds, bats, beetles, and flies among others. About three-fourths of the major food crops in the world are animal-pollinated, which directly contributes to raising crop yields, quality and nutrition. Pollinator numbers, however, are under severe pressure as the result of habitat loss, exposure to pesticides, climate shift, and monocrolting. Existence of these threats do not only pose risk to the ecological balance but also to the global food security and rural livelihoods. This review discusses the fascinating ecosystem of pollinators, their functional capacities in the agricultural environment, and the detail relationships between the health of pollinators and sustainable farming systems. It also looks at the recent issues of concern, conservation approaches and new solutions to foster pollinator-friendly farming. By stressing the necessity of implementing pollinator conservation practices as far as their infiltration into agricultural policies is concerned, the review unveils the importance of interdisciplinary research contributions to the pollinator biodiversity protection as a keystone of sustainable development.

Key words: Pollinators, stressing, biodiversity, habitat loss, pesticides, climate shift, monocrolting.

INTRODUCTION

Pollination is a requirement in terms of Criterion of the ecosystem functioning and agricultural productivity with an invaluable contribution in the reproduction of plants and global food supply (Ochola et al., 2025). Pollinators are organisms that transfer pollen from the male part (anther) of a flower to the female part (stigma), enabling fertilization and the production of seeds and fruits (Kumar et al., 2025). This process, known as pollination, is essential for the sexual reproduction of many flowering plants. There are two types of pollination. The biotically pollinated would require pollinators Over 50 percent of food crops in the world such as fruits and vegetables rely on insect pollinators (Bareke et al., 2025). The bees, moths, flies, beetles and wasps form the vast majority of such pollinators. Pollinators have an array of biological and behavioral aspects that have made them serve their causes e.g. pollinators as agents of pollination which thereby directly influences agricultural sustainability (Ali et al., 2025). Among their major characteristics is body structure. Most pollinators (particularly bees) also have a hairy body and various body parts adapted to pollen collecting, such as pollen baskets (corbicula) on the legs. Moreover, their long proboscis would enable them to reach the deep floral nectaries ensuring a contact with the part producing pollen. The second important characteristic is floral constancy, wherein pollinators are more liable to visit within-species flowers throughout a

Cite This Article as: Shoukat S, Javaid T, Arbi FUR, Afghan SS, Tariq F, Batool M, Touqeer Z and Aqsa, 2025. Animal Pollinator Assemblages: Biodiversity Dynamics and Roles in Sustainable Agro-Ecosystems. Trends in Animal and Plant Sciences 6: 177-184. https://doi.org/10.62324/TAPS/2025.092

foraging trip, raising the chance of fruit establishment and fruit set. Their high level of flight aptitude and movement has helped them to cover sprawling farmlands thereby ensuring that cross-pollination is possible among different plants acquired through long distances, thereby increasing crop variability and crop yield. Additionally, there are levels of pollinators activity that are scheduled round the day allowing the plant to be pollinated constantly, pollinators like bees and butterflies to make their visits during the day, while bats and moths as pollinators visit the plant at night. These are combined features that make pollinators a necessity in the wellbeing and the stability of the agricultural systems globally (Patil et al., 2024; Kumar et al., 2024; Katumo et al., 2022).

Since ancient times, pollination has been a crucial component to the agricultural process, even though earlier civilizations could not have realized anything about the biological process (Cai, 2025). It was discovered over time that crops relied on insects (primarily bees) and pollination began to be recognized. Science knowledge started in the 17th century with revelations of plant breeding and insect functions. In the 19th and 20th centuries, commercial beekeeping developed and boosted the productivity of the crops by providing pollination applications. Over the past few decades, pollination has been acknowledged as one of the foundations of agricultural sustainability and food security worldwide in light of this (Peixoto et al., 2022). There is growing pressure to identify the key problems facing pollination and establish the actions that should be taken to alleviate them. In short Pollinator biodiversity is vital for agricultural sustainability as it directly supports the reproduction of over one third of major food crops. Because pollinators are widely used in agricultural systems, crop yields and quality have increased dramatically, establishing them as essential components of sustainable agriculture methods. However, habitat fragmentation, pesticide abuse, and climate change are posing an increasing threat to their populations, which calls for study to maximize their ecological benefits (Rabeena et al., 2025). Global agriculture is seriously threatened by their decline as a result of habitat loss, pesticide use, and climate change. Protecting pollinators is essential for maintaining productive farming systems and ensuring long-term ecological balance.

Types and Diversity of pollinators:

Both the scientific literature and the general public place a high value on pollinators. This is partly due to the realization that plant-pollinator relationships are an intrinsically fascinating class of interactions and to well-intentioned media efforts focused at "Saving the pollinators". They are at the heart of a lot of evolutionary innovation and have significant ecological and agricultural value. As the majority of plants reproduce by seed and cause substantial levels of evolutionary variation in both the plants and the pollinators that support them (Pearse et al., 2025). They are undoubtedly one of the most significant kinds of ecological interactions in terrestrial ecosystems. For certain plants, there are mixed pollination systems that use both wind and animals, a process known as ambophily (Cabrini et al., 2025). Animals are the pollinators of the majority of blooming plants. According to a recent global estimate, a sizable portion of gymnosperms are also biotically pollinated, and 87.5% of angiosperms use invertebrates or vertebrates in this manner. However, it is evident that the diversity and relative importance of pollinators have been subjected to significant media bias and journalistic misrepresentation, with insects gaining attention that is out of proportion to their significance and conservation needs (Saunders et al., 2025). We can, however, give more precise estimates for some groups (especially birds, mammals, and most likely bees), making it gradually feasible to move towards a complete description of the total phylogenetic diversity and the number of species involved. In orchards and wild fields, 368 species from 115 families and 7 orders were found to be pollinators of 43 distinct fruits and flowers. The Hymenoptera (110 species, 373 records) were the most varied insect pollinators, followed by the Diptera (104 species, 219 reports), the Coleoptera (88 species, 111 records), and the Lepidoptera (47 species, 97 records) (Barda et al., 2023). With 34 records, the honey bee (*Apis mellifera*) was the most common insect pollinator. It was followed by *Eristalis cerealis* (Diptera), *Tetralonia nipponensis* (Hymenoptera), *Xylocopa appendiculata* (Hymenoptera), *Eristalis tenax* (Diptera), *Helophilus virgatus* (Diptera), and *Artogeia rapae* (Lepidoptera), with 12 records. Because they spend the majority of their lives gathering pollen, a source of protein that they feed to their developing progeny, and nectar, a concentrated energy source, bees (Hymenoptera) are the primary insect pollinators (Begum et al., 2023). The most well-known and extensively controlled pollinator is the honey bee. Hundreds of additional bee species, primarily solitary ground nesting species, are also crucial to natural plant ecosystems and provide some degrees of pollination services to crops. With almost 21 species, *Andrena* was the most diversified genus among bees. It was followed by *Lasioglossum* with 14 species, *Bombus* with 8 species, *Nomada* with 6 species, and *Osmia* with 5 species.

The second most significant insect order for pollination and flower visits is thought to be flies. Around the world, a variety of dipteran insects are employed professionally as pollinators for particular crops. For example, calliphorid flies are used on canola, sunflower, buckwheat, garlic, lettuce, and peppers, whereas Eristalis hoverflies are used on peppers. With five species, *Drosophila* was the most common dipteran genus in Korea. It was followed by four species of *Paragus* and three species of *Calliphora, Eristalis, Helophilus, Pipiza, Sphaerophoria,* and *Syrphus*. In Australia, Drosophilidae have been linked to

Genoplesium (Orchidaceae) pollination. In the Nearctic, Neotropical, and Australo-Pacific regions, it is known that many *Convolvulaceae, Hibiscus*, and other plants with campanulate blooms have yeasts that are spread between their blossoms by Drosophilidae and sympatric Nitidulidae (Coleoptera) (Kato, 2017).

The third varied group of insects that visited flowers were beetles. The largest group of insects, beetles pollinate 88% of the 240,000 blooming plants and a diverse variety of plant species with different reproductive characteristics (Hanberry, 2025). The flower visiting insects are found in 51% of the dipteran families (44 families) and 23% of the beetle families (28 families) throughout Australia.

Role of pollinators in agriculture

Insect pollinators are crucial for pollinating plants, visiting apple, pear, and 80 percent of all plant species in Europe and most fruits. Honey bees, specifically *Apis mellifera*, are the most dominant species. Insect pollinator diversity is expected to increase, with a direct decrease in total agricultural productivity ranging from 3 to 8% (Aizen et al., 2019). In developing countries, agricultural land shortages are causing a significant increase in cultivated areas, particularly for crops with lower yield growth. Pollinators, including bees, butterflies, birds, beetles, and bats, are crucial for the reproduction of over 75% of the world's most important food crops (Khalifa et al., 2021). Preserving biological diversity is essential for food security and ecosystem resilience. Monoculture systems, where natural pollinators are replaced by pest-control measures, habitat loss, and climate change, can lead to low yields, higher production costs, and increased dependence on managed pollination, such as commercial beekeeping. Moreover, complementarity of native vegetation and pollinators ensures sustainability of the agro-ecosystems through water, pest control and soil fertility. Farming systems that can enhance pollinator diversity, i.e. intercropping systems, organic farming systems, flowering plant planting and retention of natural uncultivated plains, ensures sustainable production systems that can better withstand ecological and economic shocks (Sati, 2024). Thus, it is not only a matter of environmental protection, but also a critical adaptation strategy needed to maintain agricultural productivity, nutritional diversity, livelihoods in many agricultural regions, and global food webs as the pace of environmental alteration continues to increase.

Interlinkages with Agricultural Sustainability:

These connections between agricultural sustainability and pollinator diversity are critical, complicated, and form the basis of sustaining the global food supplies as shown in figure 1. The most common acts of pollination in the world are by bees, butterflies, moths, wasps, flies, beetles, birds and bats, among others during which more than half of the global food crops, other than fruits and vegetables, nuts, seeds, and oil seeds, are pollinated (Milind et al., 2025). Their variability has the advantage of providing effective, timely and adequate pollination on crops and this directly influences the crop yield, quality, nutritional value and the value of the crop in the market. Ecological redundancy of pollinators implies the abundance of species to ensure that, in case of environmental stress, one species halts its reproduction process, the others will continue, hence, increasing the resilience of agricultural systems facing climate change, disease, and habitat loss among other shocks (Rhodes, 2018). Such functional diversity also aids in the pollination of crops in an expanded range of varying environmental conditions, including varying hours within the day, seasons, and weather patterns which further leads to food security and crop stability in terms of yields. In its turn, sustainable agriculture practices encourage and depend on the population of healthy pollinators. Management practices that promote suitable habitat of pollinators to be able to find shelter and food sources include the use of less pesticides (Gebhardt et al., 2025) the use of integrated pest management tools, conserved hedgerows, flower strips, fallow land, organic farming and agroforestry. These landscapes are of advantage not only to the pollinators, but also enhance the health of soil, retention and biodiversity in general hence a positive feedback cycle between the health of natural systems and agricultural outputs. The lack of pollinator diversity leads to farming systems that are more reliant on artificial inputs that are expensive in the form of managed pollination or the use of synthetic fertilizers that have also been shown to destroy ecosystems further (Khan et al., 2025). Therefore, preserving the diversity of pollinators is not just important in terms of ensuring agricultural productivity and quality, it is also a central pillar in the sustainability of the environment, rural livelihoods and food sovereignty around the world. It is important to note and intensify these inter-relationships to create a sustainable way of formulating agricultural systems that will be ecologically sustainable and economically viable to future generations. Some major pollinators, their targeted crops, and associated impacts on yield performance have been described in table 1.

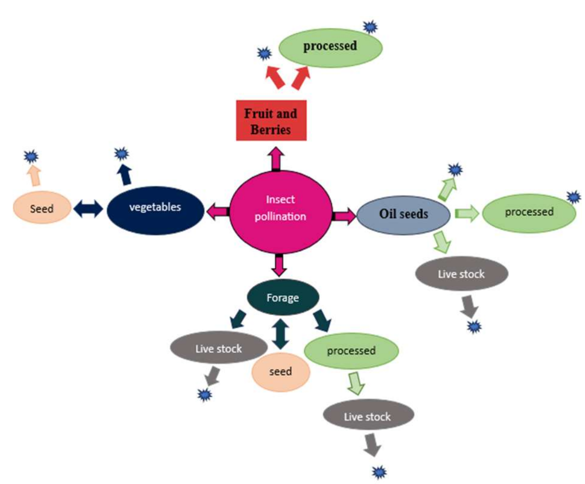

Fig. 1: The process of insect pollination and the consumer.

Table. 1: Role of pollinators in enhancing crop productivity, fruit set, seed yield and quality through pollination services.

Pollinator	Targeted Crop(s)	Overall Yield Performance	References	Notes
Bumblebees (*Bombus* spp.)	Tomato	Increase yield by 20–30% in greenhouse; improve fruit set.	Salvarrey et al., 2020	Buzz pollination advantage.
Bumblebees	Blueberry, Cranberry	Improve berry size, uniformity, and yield by ~25%.	Nicholson et al., 2019	Strong vibrational pollination.
Honeybees (*Apis* mellifera)	Apple	Boost yield and fruit set by ~20%.	Geslin et al., 2017	Widely used in orchards.
Honeybees	Almond	Essential; responsible for up to 90% fruit set.	Sáez et al., 2020	Largest managed pollination service.
Honeybees	Sunflower	Increase seed set and oil yield by 15–20%.	Karso et al., 2023	Cross-pollination vital.
Honeybees	Rapeseed / Canola	Enhance pod set and seed yield by 20–25%.	Akhatar et al., 2025	Improves oil content.
Honeybees	Cotton	Improve boll set and fiber quality (10–15%).	Paul et al., 2025	Supplemental pollination.
Stingless Bees (Meliponini)	Coffee	Increase fruit set 15–20%.	Supeno et al., 2021	Active in tropical farms.
Stingless Bees	Passionfruit	Enhance pollination success by 20%.	García, 2024	Niche tropical pollinator.
Butterflies & Moths (Lepidoptera)	Cotton, Okra	Moderate yield increase (5–10%).	Mohapatra, 2023	Useful for cross-pollination.
Butterflies & Moths	Pumpkin, Squash	Improve fruit set by 8–12%.	Haider et al., 2025	Evening/night pollination role.
Beetles (Coleoptera)	Custard Apple (*Annona*)	Fruit set up to 20%.	Romero et al., 2025	Known as "mess and soil pollinators".
Beetles	Magnolia	Enhance seed set, essential pollinators.	Sukumaran et al., 2024	Ancient pollination system.
Flies	Cabbage, Brassicas	Improve seed production 10–15%.	Wahba et al., 2025	Work well in cool climates.
Flies	Umbellifer seeds (dill, fennel, coriander)	Boost seed set by 12–20%.	Wahba et al., 2025	Often overlooked pollinators.

Threats to pollinators biodiversity

Biodiversity of the pollinators is under the threat of a wide variety of challenges, most of which occur as a result of human activities and environmental transformation. Loss and fragmentation of habitat is among the vital threats and it is brought about by the increase in urbanization, intensive agriculture, deforestation, and the development of infrastructures.

Loss of Habitat, Foraging and Nesting Resources

The transformations limit access to nesting sites, shelter and a variety of flower resources pollinators require to exist. A close companion to habitat degradation is the prevalence of agrochemicals, especially pesticides (neonicotinoids, herbicides, and fungicides), which may be detrimental to pollinators due to their toxic nature, displacement of pollinator behavior in foraging, lower abilities to succeed reproduction, and even death. The imposed threat of climate change is also an issue as it influences the flowering of plants and activity of pollinators causing the lack of synchronization between the source of nutrition and a pollinator (PRAKASH et al., 2025).

Extreme weather conditions:

Bees rely on flowers for pollen and nectar, which are essential for their survival. The average honeybee colony has around 40,000 bees, and their longevity depends on the availability of pollen, nectar, and water. However, changes in land use, landscapes, and agricultural practices have led to the decline of insect pollinators worldwide. The *Varroa Destructor* mite and global bee diseases have also impacted beekeeping and health. Stress from parasites, insecticides, and flower shortages are believed to contribute to honeybee declines. The occurrence of extreme weather conditions, the warming of climate, droughts, and alterations in the precipitation patterns and quantities are able to further add pressure to the pollinator populations and affect their life cycles (Naz, 2025). Also, native pollinators could be out-competed or eaten by invasive species (exotic plants and predatory insects), upset local ecosystems, and create novel diseases and parasites. Higher-affected diseases common with the *Nosema* spp. Varroa destroyer mites, and various virus infections are specifically devastating to manage wild bee populations that can disseminate at fast rates in areas with dense agricultural production.

Monoculture practices:

The practices of monoculture farming also lead to decline of these pollinators because of low floral diversity and food availability at a given time (established as pollinator deserts throughout low-bloom periods) (Sultana and Mondal, 2025). Contamination, such as air, light, and heavy metal contamination can disrupt the pollinators in the capacity to find their way to flowers and their surroundings. Together, the threats are reflected in the loss of pollinator abundance as well as of species richness, threatening the stability of natural ecosystems as well as the sustainability of world agriculture. These challenges can be solved with the help of urgent and organized conservation activities and the implementation of pollinator-friendly land managements (Gionfra et al., 2025).

Status of pollinators in last a few decades:

Pollinators, including bees and hoverflies, have experienced significant declines in recent decades. In the United States, bumblebee populations have decreased by up to 96%, and some of their ranges have shrunk by 23-87%. Managed honeybee populations are also declining, with the number of managed hives (Ahsan et al., 2025). Orchard farmers in China have been forced to use human hand-pollinators since the 1990s. Hand pollinators are economically ineffective and less effective than modern methods. Australia has strict quarantine regulations to prevent foreign species from disrupting honeybee populations. However, there have been increased honeybee diseases, high winter colony losses, and decreased queen longevity. Research suggests that the rise in winter colony losses is not caused by a single factor but rather by a combination of factors, including the use of systemic pesticides, climate change, invasive species, agriculture intensification (Neov et al., 2019) agrochemicals, roads, motorized traffic, and nocturnal light pollution. Because of their essential ecological role and crucial contribution to local and global food security, pollinators need special attention in this broader context.

Effects of use of agrochemicals on pollinator diversity:

The environmental transformations restrict pollinators' access to essential ecological resources, including nesting substrates, refugia, and diverse floral provisions required for their survival and reproduction. Closely associated with habitat degradation is the extensive application and persistence of agrochemicals within agricultural landscapes, especially pesticides (neonicotinoids, herbicides, and fungicides) (Naz et al., 2023) which may be detrimental to pollinators due to their toxic nature, displacement of pollinator behavior in foraging, lower abilities to succeed reproduction, and even death. The imposed threat of climate change is also an issue as it influences the flowering of plants and activity of pollinators causing the lack of synchronization between the source of nutrition and a pollinator. Particularly in agricultural areas, changes in land use and landscape have significantly decreased the quantity and variety of wild flowers. The availability and variety of wild flowers have been significantly diminished by current large-scale agriculture with huge monoculture and extensive use of herbicides (Nath et al., 2024) (Centaurea cyanus in corn fields and Persicaria maculosa in potato fields). Pollinators are adversely affected by the usage of genetically modified bulk crops in a number of ways. The widespread use of herbicides, which eradicates flowering weeds and weeds that serve as host plants from the agricultural landscape, is closely correlated with the development of herbicide-tolerant genetically modified crops. Genetically modified crops that are resistant to insects, like those that produce *Bacillus thuringiensis* (Bt) toxins, may lessen the need for insecticides and ease the burden on certain pollinators, like bees, but they may also negatively affect other pollinators, like some butterflies. Because nitrogen buildup decreases the variety and abundance of flowering plants in the landscape, it has an impact on pollinators.

Large-Scale Prophylactic Use of Systemic Neonicotinoid Insecticides

Neonicotinoids, a new class of pesticides, were introduced in the early 1990s and have lower acute toxicity compared to older insecticides. They are commonly used in soil treatments, agricultural seeds, and genetically modified crops (Łukaszewicz et al., 2025). These neurotoxic agrochemicals work systemically, absorbing active ingredients through roots and making plants poisonous to insects. Imidacloprid, the most commonly used neonicotinoid, is over 7,000 times more harmful to honeybees than DDT and has behavior-disturbing effects on non-target insect species (Ganguly and Banerjee, 2025). It can cause behavioral disruptions and can be deadly with extended exposure. Synergistic effects with other agrochemicals have also been reported.

Effects of decline of pollinators biodiversity:

Reduced Crop Yields

The decline of pollinators has direct effects on crop yields mostly in the case of crops that are highly dependent on pollination. A decline in the populations of pollinators can cause decline of fruit set and seed production, and consequent food insecurity (Bogdziewicz et al., 2025).

Increased Dependence on Artificial Pollination

In areas with a low population of pollinators, farmers can make use of measures of artificial pollination either by hand-pollinating or by artificial pollination services (Sagili et al., 2025). Though these methods may boost crop yields, but they are short-term and economically unaffordable.

Disruption of Biodiversity

The loss of pollinators due to pollinator decline does not only impact crop production but also upsets a wider ecological balance. The loss of pollinators results in the decline of wild plants, which are important for maintaining ecosystem services and supporting biodiversity (Babu et al., 2025).

Benefits of Pollinator Conservation

Conservation of the pollinators means that crops obtain proper pollination which result in better crop yields and food quality. This helps in addition to greater food security and less artificial means of pollination. Protecting the pollinators will ensure that there is biodiversity in the ecosystem to support the existence of different plants and animal species. Pollinators are part of ecology and their well-being improves the health of the environment in general. The economic activities of pollinator conservation can prove to be very prosperous as the expenditure incurred in usage of artificial pollination, (Rong et al, 2025) improvement in crop production and profitability of industries that depend on the pollination of their crops are much more than the conservation costs of pollinators.

Challenges in Pollinator Conservation

Awareness is one of the main impediments that face pollinator conservation because the society is not informed about the significance of pollinators. To continue to bring change, it is necessary to create awareness and educate stakeholders of the reason why they need to protect the pollinators. Efforts to preserve pollinators may involve financial outlay in the form of restoration of habitats, sustainable agricultural methods and enforcement of related policies. They require huge funds to finance these projects in regions with scarce resources and this can be a big challenge.

Future Directions for Pollinator Conservation

The research direction must be aimed at hospitals in investing in the knowledge of the determinants of the decline of pollinators and effective ways of protecting them. Researchers, farmers, environmentalists, and policymakers will have to collaborate to find comprehensive solutions to help pollinators sanctuaries. Such technological breakthroughs as observation and data processing systems can be used to monitor pollinator populations, evaluate the quality of their habitats, and maximize conservation efforts. Technology deployment will also become more significant to safeguard pollinators and to make Agri-systems sustainable.

Conclusions

Overall, it is concluded that decline of pollinators has a big impact on the sustainability of the agricultural sector and food security. By appreciating the importance of pollinators in crop production and factors that contribute to the decline in pollinators, we are able to develop powerful strategies which can conserve the pollinators. These strategies include rehabilitating habitat, sustainable agriculture, and policy encouragement. we can be sure that pollinators will thrive to continue with their vital and critical role of agricultural productivity and enhancing the health of other ecosystems. To achieve agricultural sustainability, it is recommended multidimensional strategies that include (1) constructing pollinators-friendly agroecological landscapes by connecting fragmented habitats through ecological corridors and promoting diversified cropping systems; (2) enforcing stringent controls on neonicotinoid pesticides and implementing dynamic chemical risk assessment protocols; and (3) advancing commercial pollinators rearing via policy incentives to ensure stable pollination services. These measures must be embedded within global agricultural policy frameworks and refined through interdisciplinary collaboration.

DECLARATIONS

Funding: There was no funding to carry out this research.

Acknowledgement: The authors gratefully acknowledge the Department of Zoology, Government College Women University Faisalabad, Department of Zoology, Wildlife and Fisheries, University of Agriculture Faisalabad, Pakistan and Department of Microbiology, University of Haripur, for providing the necessary facilities, resources, and technical support to carry out this research.

Conflict of Interest: The authors declare that there is no known conflict of interest associated with this publication.

Data Availability: The data will be available upon request to the corresponding authors.

Ethics Statement: All animal studies have been approved by the relevant ethics committee or institutional supervisory board and have been conducted in accordance with the ethical standards.

Author's Contribution: SS, TJ, FURA, conducted experiments on quails, analysis and generalization of experimental data. SSA, FT, conducted chemical and amino acid analysis of feed reactions. MB, ZT and A developed a methodological part of the studies. Conducted experiments on the analysis of the raw material and enzymatic hydrolysis of lupine, analyzed the experimental data, designed the article. The final draft manuscript was revised by all authors. All authors edited, read, and approved the final manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

REFERENCES

Ahsan, Z., Wu, Z., Lin, Z., Ji, T., & Wang, K. (2025). The Sublethal Effects of Neonicotinoids on Honeybees. *Biology*, *14*(8), 1076.

Aizen, M. A., Aguiar, S., Biesmeijer, J. C., Garibaldi, L. A., Inouye, D. W., Jung, C., ... & Seymour, C. L. (2019). Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global change biology*, *25*(10), 3516-3527.

Akhatar, J., Upadhyay, P., & Kumar, H. (2025). Crop cultivation and hybrid seed production strategies in rapeseed-mustard. In A. Lamichaney, A. K. Parihar, A. Bohra, P. Karmakar, & S. J. S. Naik (Eds.), *Hybrid seed production for boosting crop yields: Applications, challenges and opportunities*,1 (pp. 177–224). Springer Nature Singapore, Singapore.

Ali, M., Khan, F. Z. A., & Ahmad, M. A. (2025). Insect pollinators and food security under the changing climate. In M. Behnassi, M. B. Baig, H. Gupta, R. Sabbahi, G. N. Gill, & M. El Haiba (Eds.), *Food systems and biodiversity in the context of environmental and climate risks: Dynamics and evolving solutions*, 1 (pp. 263–293). Cham, Switzerland: Springer Nature Switzerland.

Babu, S., Niveditha, E. A., Sooraj Dev, K., & Shamil Haque, K. M. (2025). Forest degradation: Loss of biodiversity and ecosystem services. In G. Shukla, A. Manohar K., A. R. Kizha, P. Panwar, & S. Chakravarty (Eds.), *Forest degradation and management: An Indian perspective,* 1 (pp. 125–137). Cham, Switzerland: Springer Nature Switzerland.

Bareke, T., Alemu, T., Addi, A., Yimer, O., & Mengesha, D. (2025). Effects of honeybee pollination and other insect pollinators on increasing the seed yield and germination capacity of carrot (Daucus Carota L.) in the central highlands of Ethiopia. *BMC plant biology*, *25*(1), 1051.

Begum, H. A., Idrees, A., Afzal, A., Iqbal, J., Qadir, Z. A., Shahzad, M. F., ... & Li, J. (2023). Impact of different pollen protein diets on the physiology of Apis mellifera L. (Hymenoptera: Apidae) workers from essential plant sources. *Journal of King Saud University-Science*, *35*(2), 102511.

Bogdziewicz, M., Kelly, D., Zwolak, R., Szymkowiak, J., & Hacket-Pain, A. (2025). Dynamics, Mechanisms, and Consequences of Mast Seeding. *Annual Review of Ecology, Evolution, and Systematics*, 56. https://doi.org/10.1146/annurev-ecolsys-102723-052948

Cabrini, M., Paglia, I., Pinto, A. R., Lira, C., & Trovó, M. (2025). Ambophily ensures high reproductive success in a generalist species: Paepalanthus calvus (Eriocaulaceae) as study case. *Brazilian Journal of Botany*, *48*(1), 25.

Cai, W. (2025). Continuing the Path of Green Income Growth to Realize the Dream of Industrial Revitalization. *Bioscience Methods*, *16*. doi: 10.5376/bm.2025.16.0012

Ganguly, P., & Banerjee, K. (2025). Pesticide in food chain: Impact and regulation. In D. Mondal & M. Mahmudur Rahman (Eds.), *Food toxicity and safety,* 1 (pp. 59–76). Springer Nature Singapore, Singapore

García, M. T. A. (2024). Floral biology, pollinators and breeding system of Passiflora chrysophylla (Passifloraceae), a South American passion vine. *Australian Journal of Botany*, 72(6). https://doi.org/10.1071/BT24016

Gebhardt, S., van Dijk, J., Lof, M. E., Wassen, M. J., & Bakker, M. (2025). Understanding interactive effects between habitat configuration and pesticide use for pollination: towards better informed landscape management. *Ecological Processes*, *14*(1), 25.

Geslin, B., Aizen, M. A., Garcia, N., Pereira, A. J., Vaissière, B. E., & Garibaldi, L. A. (2017). The impact of honey bee colony quality on crop yield and farmers' profit in apples and pears. *Agriculture, ecosystems & environment*, 248, 153-161.

Gionfra, S., Cividino, R., Damiens, F., & Van Der Wal, R. (2025). Towards pollinator-friendly policy and practices: worldviews, opportunities and barriers. DOI: https://doi.org/10.5281/zenodo.14904853

Haider, G., Iqbal, S., Farooq, U., Noor, F., Majeed, M. Z., & Dawood, M. (2025). Effect of Different Insect Pollinators Conservation Strategies on Fruit Yield Parameters of Pumpkin Cucurbita pepo L. *Sarhad Journal of Agriculture*, 41(2), 476-482.

Hanberry, B. B. (2025). Potential expanded pollinator distributions in North America under future climate. *Ecological Solutions and Evidence*, 6(2), e70025.

Karso, B. A., Dabash, A. H., & Bas, S. M. A. (2023, July). The effect of honeybee for increasing of sunflower productivity. *IOP Conference Series: Earth and Environmental Science, 1213*(1), 012057. https://doi.org/10.1088/1755-1315/1213/1/012057

Kato, M. (2017). History and natural history of plants and their associates. In *Obligate pollination mutualism,* 1 (pp. 7-61), Springer Japan, Tokyo.

Katumo, D. M., Liang, H., Ochola, A. C., Lv, M., Wang, Q. F., & Yang, C. F. (2022). Pollinator diversity benefits natural and agricultural ecosystems, environmental health, and human welfare. *Plant Diversity*, *44*(5), 429-435.

Khalifa, S. A., Elshafiey, E. H., Shetaia, A. A., El-Wahed, A. A. A., Algethami, A. F., Musharraf, S. G., ... & El-Seedi, H. R. (2021). Overview of bee pollination and its economic value for crop production. *Insects*, *12*(8), 688.

Khan, F. Z. A., Ali, M., & Khan, D. H. (2025). Integrated pest and pollinator management under the changing climate. In M. Behnassi, M. B. Baig, H. Gupta, R. Sabbahi, G. N. Gill, & M. El Haiba (Eds.), *Food systems and biodiversity in the context of environmental and climate risks: Dynamics and evolving solutions,* 1 (pp. 295–316). Springer Nature Switzerland, Cham, Switzerland.

Kumar, R., Hajam, Y. A., Kumar, I., & Neelam. (2024). Insect pollinators' diversity in the Himalayan region: Their role in agriculture and sustainable development. In R. C. Sobti (Ed.), *Role of science and technology for sustainable future: Sustainable development: A primary goal,* 1 (pp. 243–276). Springer Nature Singapore, Singapore.

Kumar, S., Kumaraswamy, H. S., & Paul, D. (2025). Floral biology and pollination systems for hybrid seed production in plants. In A. Lamichaney, A. K. Parihar, A. Bohra, P. Karmakar, & S. J. Satheesh Naik (Eds.), *Hybrid seed production for boosting crop yields: Applications, challenges and opportunities* 1 (pp. 13-39). Springer Nature Singapore, Singapore.

Łukaszewicz, P., Cholewa, R., & Haliński, Ł. P. (2025). Limited evidence for interactions between neonicotinoids and humic substances in water under environmentally realistic conditions. *Microchemical Journal*,114938. https://doi.org/10.1016/j.microc.2025.114938

Milind, D. J., Dheeraj, A. S., Alpesh, H. W., Prashant, S. G., & Wajid, H. (2025). Pollinator Crisis: The Role of Bees, Bats, and Butterflies in Food Security. *Biology, Agriculture, SciTech and Environment*, 5, 01-08. https://www.basecongress.com/ebase.html

Mohapatra, S. (2023). Evaluation of various pest management modules for insect pest complex in okra, Abelmoschus esculentus (L.) Moench (Doctoral dissertation, Department of Entomology, OUAT, Bhubaneswar).

Nath, C. P., Singh, R. G., Choudhary, V. K., Datta, D., Nandan, R., & Singh, S. S. (2024). Challenges and alternatives of herbicide-based weed management. *Agronomy*, *14*(1), 126.

Naz, M. (2025). Impact of Climate Change on Plant Phenology and Distribution in Pakistan. *Review Journal of Social Psychology & Social Works*, *3*(3), 849-863.

Naz, S., Iqbal, S. S., Manan, A., Chatha, M., & Zia, M. (2023). The web of life: role of pesticides in the biodiversity decline. *International Journal of Forest Sciences*, *3*(2), 72-94.

Neov, B., Georgieva, A., Shumkova, R., Radoslavov, G., & Hristov, P. (2019). Biotic and abiotic factors associated with colonies mortalities of managed honey bee (Apis mellifera). *Diversity*, *11*(12), 237.

Nicholson, C. C., & Ricketts, T. H. (2019). Wild pollinators improve production, uniformity, and timing of blueberry crops. *Agriculture, Ecosystems & Environment*, 272, 29-37.

Ochola, A. C., Njoroge, D. M., Shao, X. L., Gituru, R. W., Wang, Q. F., & Yang, C. F. (2025). Global meta-analysis shows an indispensable role of pollinator diversity in promoting fruit quality. *Agriculture, Ecosystems & Environment*, *393*, 109829.

Patil, P. B., Rajah, R. A., Bora, N. R., Brahma, D., Krishnan, S. N., Vasanth, V., ... & Nitish, G. (2024). Pollination ecology: Understanding plant-pollinator relationships. *International Journal of Agricultural Research*, *7*, 101-105.

Paul, D., Dutta, S., Nidhi, Sapna, Jha, R., Biswas, N., & Kumar, R. (2025). Heterosis breeding and hybrid seed production in cotton. In A. Lamichaney, A. K. Parihar, A. Bohra, P. Karmakar, & S. J. Satheesh Naik (Eds.), *Hybrid seed production for boosting crop yields: Applications, challenges and opportunities, 1* (pp. 225–246). Springer Nature Singapore, Singapore.

Pearse, I. S., Becker, Z., Ode, P. J., Gaskin, J. F., & West, N. M. (2025). Low genetic diversity in populations of a clonal invasive plant limits sexual reproduction. *American Journal of Botany*, e70083. https://doi.org/10.1002/ajb2.70083

Peixoto, P. G., Martins, H. L., Pinto, B. C., Franco, A. L., Amaral, L. S., & Castro, C. V. D. (2022). The significance of pollination for global food production and the guarantee of nutritional security: a literature review. *Environmental Sciences Proceedings*, *15*(1), 7.

Prakash, A., Shrivastava, S., Joshi, R. C., & Rao, J. (2025). Impacts of global warming on insect pollinator performance and plant-pollinator interactions: a review. *Journal of Applied Zoological Researches*, *1*, 4-29.

Rabeena, I., Akash, A., Pragathy, S., & Infant, A. L. (2025). The Warming Threat: Climate Change is Devastating Honeybee Populations. *Asian Journal of Environment & Ecology*, *24*(7), 263-275.

Rhodes, C. J. (2018). Pollinator decline–an ecological calamity in the making? *Science progress*, *101*(2), 121-160.

Romero, H., Aquilino, M., Planelló, R., & de la Peña, E. (2025). Plant–arthropod associations in custard apples, genus Annona: A global perspective. *Entomologia Experimentalis et Applicata*, 173(7), 651-660.

Rong, Z., Cliquet, A., & He, M. (2025). The private non-state actor financing mechanism for restoration under the Convention on Biological Diversity: The case of China. *Review of European, Comparative & International Environmental Law*, *34*(2), 450-470.

Sáez, A., Aizen, M. A., Medici, S., Viel, M., Villalobos, E., & Negri, P. (2020). Bees increase crop yield in an alleged pollinator-independent almond variety. *Scientific reports*, 10(1), 3177.

Sagili, R. R., Chakrabarti, P., Melathopoulos, A., Delaplane, K. S., Dag, A., Danka, R. G., ... & Steinhauer, N. (2025). Standard methods for pollination research with Apis mellifera 2.0. *Journal of Apicultural Research*, *64*(2), 612-646.

Salvarrey, S., Santos, E., Arbulo, N., Gimenéz, G., & Invernizzi, C. (2020). Characteristics of the tomato fruit (Solanum lycopersicum) using native bumblebees (Bombus atratus) as pollinators in greenhouse. *Agrociencia (Uruguay)*, 24(1). https://doi.org/10.31285/agro.24.101

Sati, V. P. (2024). Farming systems and sustainable agriculture. In V. P. Sati (Ed.), *Farming systems and sustainable agriculture in the Himalaya, 1* (pp. 49–62). Springer Nature Switzerland, Cham, Switzerland.

Saunders, M. E., Lees, A. C., & Grames, E. M. (2025). Understanding and counteracting the denial of insect biodiversity loss. *Current opinion in insect science*, *68*, 101338.

Sukumaran, A., Khanduri, V. P., Gairola, S., & Sharma, C. M. (2024). Floral traits and functional role of whorls in pollinator attraction of Magnolia grandiflora L. *Folia Oecologica*, 51(2), 263-274.

Sultana, A., & Mondal, S. (2025). Role of insect pollinators in world economy. In A. Rajpurohit & N. Kachhwaha (Eds.), *Essentials of economic entomology,* 6 (pp.1-57). AkiNik Publications, New Delhi, India.

Supeno, B., Erwan, E., & Agussalim, A. (2021). Enhances production of coffee (Coffea robusta): The role of pollinator, forages potency, and honey production from Tetragonula sp. (Meliponinae) in Central Lombok, Indonesia. *Biodiversitas Journal of Biological Diversity*, 22(10). https://doi.org/10.13057/biodiv/d221062

Wahba, M. M., Abedin, M. A., Alhaithloul, H. A., Alghanem, S. M., & Elshamy, M. M. (2025). Advances in dill (*Anethum graveolens* L.) molecular breeding strategies. In J. M. Al-Khayri, S. M. Jain, & S. Penna (Eds.), *Biodiversity and genetic improvement of herbs and spices*, 8 (pp. 89–120). Springer Nature Switzerland, Cham, Switzerland.