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REVIEW ARTICLE

Climate-Smart Pollinator Management: Integrating Biodiversity, Technology, and Sustainable Farming

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ABSTRACT

Pollinators play an essential role in both agriculture and natural ecosystems, facilitating the reproduction of over 75% of global food crops and nearly 90% of flowering plant species. Despite their critical importance, pollinator diversity is experiencing alarming declines due to climate change, habitat loss, and the pervasive use of agrochemicals. Currently, approximately 40% of invertebrate pollinators including bees and butterflies are at risk of extinction, posing serious threats to biodiversity, agricultural productivity, and global food security. In response to these converging challenges, this review explores the concept of climate-smart pollinator management, which integrates biodiversity-based farming practices, emerging technologies, and adaptive policy frameworks. Ecologically grounded strategies such as agroforestry, wildflower strips, and diversified cropping systems can restore pollinator habitats and enhance landscape-level resilience. At the same time, technological innovations including remote sensing, IoT-enabled sensor networks, smart hives, computer vision, and edge computing offer powerful tools for real-time monitoring and data-driven management of pollinator populations, while minimizing reliance on harmful agrochemicals. Integrating pollinator conservation into the broader framework of Climate-Smart Agriculture (CSA) strengthens sustainable farming systems by optimizing resource use, reducing pesticide exposure, and enhancing crop resilience under changing climatic conditions. This review synthesizes interdisciplinary insights from ecology, agricultural technology, and policy to identify systemic pathways toward pollinator-friendly and climate-resilient food systems. The paper concludes by highlighting key challenges including persistent data gaps, technological access barriers, and fragmented governance and outlines future directions that emphasize long-term ecological monitoring, advanced modeling tools, cross-sectorial collaboration, digital innovation, and inclusive policy design. Climate-smart pollinator management thus emerges as a scalable and strategic blueprint for ensuring biodiversity conservation, agricultural sustainability, and food system resilience in an era of global change.

Key words: Pollinators, Biodiversity, Climate-Smart Agriculture (CSA), Pollinator conservation, Emerging technologies, Pollinator decline

INTRODUCTION

Pollinators play a crucial role in sustaining ecosystems by facilitating the reproduction of both agricultural crops and wild plant species (Artamendi et al., 2025). In recent years, alarming declines in pollinator populations have been reported globally, posing a serious threat to food security, as approximately 75% of crop species depend on animal-mediated pollination (López-i-Gelats et al., 2025). Pollinators contribute to this process by transferring pollen from one flower to another, enhancing genetic diversity and improving yield quality in many crops (Chabert et al., 2024). Successful pollination ensures the development of healthy fruits and viable seeds, thereby enabling plant reproduction and sustaining biodiversity (Lakra et al., 2025). Globally, present pollinators that help in pollination are bees, butterflies, moths, beetles, ants, and wasps (Devi et al., 2024). Among flowering plants, approximately 95% rely on cross-pollination, with 85% of this service performed by these pollinator species (Artamendi et al., 2025). Honeybee is the major pollinator that pollinated more than 90% of the flowering plants (Rahimi & Jung, 2025).

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In return for their pollination services, pollinators obtain nectar from flowers, which provides essential nutrients such as carbohydrates, proteins, lipids, minerals, and essential oils especially important for the health and nourishment of honeybees (Ansaloni et al., 2025). However, numerous studies indicate that about 41% of pollinator species are currently in decline and one-third are at risk of extinction (Cornelisse et al., 2025).

Pollinator diversity plays a vital role in enhancing pollination services, contributing significantly to crop productivity and ecosystem resilience (Diyaolu & Folarin, 2024). However, increased agricultural intensification often leads to a decline in this diversity (Burian et al., 2024). The implementation and proper management of agroforestry systems can counteract these negative effects, promoting the restoration and enhancement of pollinator diversity (Garibaldi et al., 2017; Jose, 2009). To safeguard both pollinator populations and food production, the conservation of natural habitats must be prioritized through the development and enforcement of sustainable public policies (Potts, Imperatriz-Fonseca, et al., 2016). These measures are essential in ensuring maintenance of the ecological balance that is necessary to have effective pollination. Socioeconomic systems mainly depend on the ecosystem services, which directly or indirectly provide vital services like food, fiber, clean water and air (MEa, 2005). These services play a fundamental role in supporting the state of human well-being and health and therefore it becomes paramount to conserve and preserve biodiversity through a holistic approach of managing the environment (IPBES, 2019). Cape Floristic Region (CFR) acts as a diversity center to a range of pollinator groupings such as the bees and is played out as registering remarkable high-levels of plant and animal species richness and endemism (Turpie et al., 2007). Researches have also shown that there is much more diversity of bee species in the quality of natural habitat in the CFR as opposed to the conventional and organic farming regions (Adedoja, 2019).

The decline is mainly a result of the human induced disaster namely, destruction of the habitat, pollution, and etcetera new farming practices (Goulson et al., 2015). Despite the attempt to increase the yields with genetically modified (GM) crops, these may be harmful to other species, such as the pollinators (Hilbeck & Otto, 2015). Also, the exponential application of chemical pesticides and herbicides, e.g., imidacloprid, thiamethoxam, clothianidin, and glyphosate, to crops is known to cause deterioration to pollinators, particularly honeybees (Blacquiere et al., 2012). The other threats are deforestation, urban spread and industrialization, loss of buffer zone, livestock grazing and intensified farming (Potts et al., 2010). Climate change adds more pressure on these forces by messing up the dance of timing between plants and pollinators and changing the environment on which they depend; Metals such as heavy metals are also a worry because the insects can absorb it in nectar which could be taken during overwintering (Forrest, 2017; Xun et al., 2018). When such patterns continue to happen, then the pollinator population decline is bound to cause the decline in pollination services hence seed and fruit production, plant regeneration, the level of inbreeding when the species is self-compatible, as well as premature pistil aging and subsequent failure of beekeeping industries within those regions (Goulson et al., 2015).

To safeguard pollinators, it is essential to ensure that they are provided with high-quality habitats that contain floral resources, nesting places, etc. These elements are indispensable in the provision of pollinators at their different stages of life (Decourtye et al., 2010). It is possible to do this in the area of nesting opportunities by reducing soil tillage and expanding vegetation cover. To illustrate, residential areas have private gardens which contributes or influence survival and reproduction of the local pollinators (Baldock et al., 2015). The plant diversity can also be implemented by planting flowering plants through early spring and late fall to provide food in the season that the pollinators are able to move (Winfree et al., 2009). The pollinators have problems in surviving without diverse flora resources. Some of the groups which provide information on non-chemical methods of controlling harmful insects that also reduce threats to the pollinators include the Coalition of alternatives to pesticides (CAP) and the California invasive bacteria and resistance council (CIBRC) (Menz et al., 2011). There also should be government involvement promoting the protection of native and wild pollinators should be followed in legislation. The Pest Control Products act which is supervised by the Pest Management Regulatory Agency (PMRA) can be amended to check the toxic impact of pesticides especially on bees (Bhuller et al., 2021). Also, governments ought to set up scientific committees that are independent so that they can determine the lethal and sub-lethal effects of different pesticides on pollinators. Strategic plans have to be implemented nationally to secure the long term survival of wild pollinators. Some of the plans that need to be formulated include the establishment of skills for the pollinator taxonomy, study of plant-pollinator relationship and safeguard of sustainable agricultural landscapes and pollinator habitat restoration (Tolera & Ballantyne, 2021).

These agroforestry systems play a critical role in the augmentation of agricultural production, food and nutritional security, conservation of natural resources and offset negative impact of climate change (Jose, 2009). Crucial ecosystem services are enabled by such systems that include crop pollination and biological pest control through the promotion of pollinators and other beneficial insects (Garibaldi et al., 2017). Agroforestry is an agricultural practice of including Arboricultural components in agricultural or pastoral fields. The benefits of agroforestry are multifaceted in environmental, economic and social spaces of sustainability (Nair, 2011). Practices, including windbreaks, hedgerow, riparian buffer, and alley cropping are extremely crucial to pollinators as they provide forage, shelter, nesting areas as well as egg lying within the temperate regions (Schroth et al., 2004). It is also through these systems that human livelihoods are made as through it people get food, nuts, fuel wood and other important resources. The practices that promote pollinator welfare contribute positively to the pollination services and help in creating more resilient and sustainable agricultural landscapes in the future since they are the synergies.

To enhance agricultural production and guarantee the food security, more particularly in climate change circumstances, modern and technology based measures have become the necessity (Kay et al., 2022). Computer vision technologies, especially, provide the improved opportunities of spatial monitoring and analysis of insect behavior, which makes it possible to have a precision in agricultural practices. The recent sampling and insect monitoring methods have been very important and helpful in giving an understanding concerning pollinator activity that is important in pollination of crops and flowering plants. The novel technologies like the Internet of Things (IoT) consisting of cheap cameras and tiny sensors attached to insects have greatly enhanced the monitoring of the pollination process. The sensors allow tracking the insects that are tagged in real-time and computer vision and deep learning models allow monitoring untagged insects (Kaur et al., 2023).

Computer vision systems, particularly in large-scale agricultural settings, capture video footage of unmarked insects and facilitate multi-species motion tracking, insect counting, and behavior analysis (Ratnayake et al., 2021). Recent advancements in deep learning and computer vision have led to their increased application in agriculture, aiding in tasks such as yield estimation, fruit counting, and the monitoring of both beneficial and harmful insects (Kamilaris & Prenafeta-Boldú, 2018).

The objectives of this review is seeks to discuss the ecological significance of pollinators in natural as well as agricultural ecosystems highlighting on their major roles in promoting diversity, agricultural productivity and the delivery of key services to the ecosystem. It tries to name the and answer the primary causes of pollinator decline such as climate change, habitat destruction, intensity of agricultural efforts, extensive use of pesticides and urbanization. The paper discusses biodiversity-based, agro-ecological approaches-agroforestry, hedgerow planting, and schemes with wildflowers in strips to the conservation of pollinators and the enhancement of habitats at the landscape level. It also evaluates the opportunities and constrains of upcoming technologies, such as IoT-enabled sensors, smart beehives, computer vision, and deep learning, when it comes to the real time tracking and accurate handling of pollinator populations. The reviewed literature also compares current policy architecture and governance issues surrounding pollinator protection and suggests the integration and adaptive approaches to policies in terms of ecological, technological, and socio-economic views. Moreover, it creates awareness of the importance of inter-disciplinary and trans-sectorial cooperation to design scalable, long-lasting resilient solutions to pollinator's management.

Pollinator Diversity and role of Ecosystem

The loss of biodiversity represents a critical ecological challenge, with pollinators at the center of concern. As primary vectors of multiple ecosystem services, pollinators play a vital role in agricultural productivity and environmental health (Potts et al., 2010). Despite their importance, the contribution of wild pollinators to agricultural yield is often under recognized by farming communities worldwide (Garibaldi et al., 2013). In agro-ecosystems, pollinators contribute to the quality and quantity of crop yields, environmental sustainability, cultural heritage, and aesthetic values (AM, 2007). Plant–pollinator interactions are essential for global biodiversity and agricultural production, with approximately 87% of flowering plants and 90% of global food crops depending on animal-mediated pollination (Ollerton et al., 2011; Rader et al., 2016). Among pollinators, insect orders like Lepidoptera, Coleoptera, and Hymenoptera are the most divergent and large groups. In contrast, Diptera and Thysanoptera are less diverse in their pollination roles (Michener, 2007). While vertebrates such as birds and bats are also effective pollinators, they receive less attention compared to bees and butterflies (Geerts et al., 2020). However, a majority of farmers globally have limited knowledge of pollinator diversity and tend to rely solely on honeybees for crop pollination (Porto et al., 2020). The reproductive success of plants, particularly in seed production, is heavily dependent on pollinator visitation. Plants visited by a wider range of pollinators generally produce seeds of superior quality and quantity (Fontaine et al., 2006).

Pollinator diversity is integral across multiple domains: natural ecosystems it supports pollination and enhances genetic diversity (Kremen et al., 2007); agricultural systems it improves fruit set and yield quality in crops such as apples, almonds, coffee, rapeseed, and cotton (AM, 2007; Garibaldi et al., 2013); environmental safety many pollinators act as natural pest and disease vectors or serve as ecological indicators (Winfree et al., 2009); cultural and aesthetic value moths and butterflies inspire art and literature (Baldock et al., 2015); honeybees are traditionally used in medicine; bats, bees, and wasps hold aesthetic importance (Papa et al., 2022). Human diets and nutrition are closely linked to their services, as we rely on pollinators for nearly every bite of food and sip of drink we consume (Gallai & Vaissière, 2009). Due to

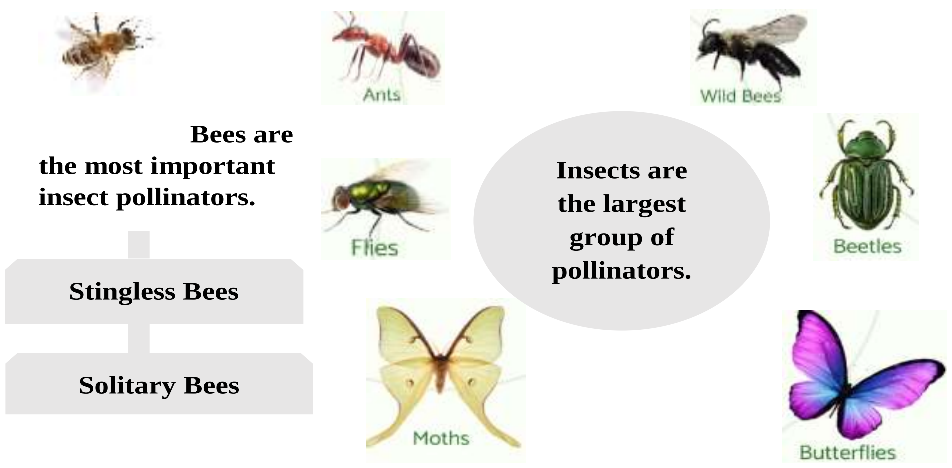

Fig. 1: Contribution of insect pollinator in pollination.

their sensitivity to environmental pollutants, bees and butterflies are often employed as bio-indicators to monitor ecological changes (Rollin et al., 2016). Similarly, bats, which forage over wide geographic ranges and accumulate trace metals through nectar consumption, also serve as valuable indicators of ecological health. This diagram shows the contribution of different pollinators in pollination (Kunz et al., 2011).

Due to their sensitivity to environmental pollutants, bees and butterflies are often employed as bio-indicators to monitor ecological changes (Chowdhury et al., 2023). Similarly, bats, which forage over wide geographic ranges and accumulate trace metals through nectar consumption, also serve as valuable indicators of ecological health. Additionally, many insect pollinators function as natural enemies to crop pests such as cereal leaf beetles and aphids, contributing to biological pest control (Nicholls & Altieri, 2013). Urban expansion, especially in developing countries, poses a significant threat to arable land and biodiversity. With nearly half of the global population now residing in urban areas, the preservation of green spaces such as forests, gardens, parks, roadsides, riverbanks, and green rooftops is increasingly important (Leeson, 2018). These green areas provide essential nesting and foraging habitats for pollinators and studies have shown a positive correlation between the abundance of pollinators and the presence of such urban green spaces (Baldock et al., 2015).

Climate change directly threatens the food security of the planet and has a significant impact on the extinction of biodiversity, mainly due to direct agricultural activities (Lee et al., 2023). There are key agricultural and ecosystem services that are supported by biodiversity in ensuring food production (MEa, 2005). CSA is a multi-faceted solution that responds to multiple dimensions of agriculture, including farm level activities, supply chains, all the way to policy levels, with the overarching goal to define an agricultural operation that is environmentally-friendly and able to adapt to the changing conditions. CSA is underpinned by three primary objectives, which include: creation of reduction of greenhouse emission, enhancement of productivity within agriculture, and alleviation of the resilience of food systems to climate change (Ouda & Zohry, 2022).

A case study in the East Usambara Mountains of Tanzania has been used to determine the effects of CSA practices with the traditional farming approach in control of pests, natural biodiversity, and yield and crop damage. The researchers indicated that all of the commonly applied CSA methods in the region, including terracing, trenching, live mulch and compost mulch, were the most effective strategies in keeping the pests at bay, augmenting food production, and promoting better agricultural revenue (Maurice et al., 2022). The findings also underscored that diverse combinations of management practices produce varying biodiversity outcomes, often involving trade-offs. Importantly, the research emphasized that local management strategies, neighboring farm practices, and broader landscape features all significantly influence the ecological and economic success of CSA implementation (Lipper et al., 2014).

Climate Change Impact on Pollinators

Over the past two decades, global temperatures have risen by more than 1.5°C, posing a significant threat to global food security and agricultural productivity (Lee et al., 2023). One of the major anxieties is the loss of natural habitats due to rapid land-use changes driven by human activities (Potts et al., 2010). It is projected that by 2050, agricultural production will need to double to meet the demands of the growing global population (Boliko, 2019). According to FAO data (1962–2006), crop yields of pollinator-dependent plants decreased by an estimated 3–8% in the absence of pollinators (Aizen et al., 2009). Studies have shown that agricultural productivity is declining in many regions, particularly in temperate and tropical areas, where climate change significantly affects major cereal crops such as wheat, corn, rice, and soybean (Lobell et al., 2011; Wheeler & Von Braun, 2013). Crops are categorized into four groups based on their dependency on pollinators: (1) Essential – production decreases by over 90% without pollination; (2) High – production declines between 40–90%; (3) Modest – production declines between 10–40%; and (4)

Little – production is reduced by 0–10% in the absence of pollination (AM, 2007). Of the 87 pollinator-dependent crops, 13 are classified as essential, 30 as highly dependent, and 27 as modestly dependent (Aizen et al., 2009). These figures highlight the critical role that pollinators play in ensuring global food security and sustaining agricultural productivity.

Research has predominantly focused on abiotic processes over biotic interactions in understanding species distribution patterns (Forrest, 2015). Elevation is frequently employed as a proxy for climate, as abiotic factors such as temperature, precipitation, and solar radiation can vary significantly over relatively short vertical distances (Körner, 2007). Alpine and sub-alpine ecosystems, which exist at high elevations, are particularly sensitive to climatic shifts, with alpine environments experiencing some of the most pronounced impacts of climate change (Rixen et al., 2022). Weather refers to the short-term variations in the abiotic environmental variables whereas the climate refers to the long-term average of the weather; the climate acts as a major determinant in the organization of the ecosystems and the population dynamics of the species (Parmesan, 2006). Weather influences several features in pollinator biology as the time of emergence, feeding, mating, migration patterns and mortality levels. On the other hand, climate affects the pollinators across several generations and this affects their range, community structure, physiology and composition (Forrest & Thomson, 2011).

The plant-pollinator relationship has been largely interfered with by climate change which increases its temperature, changes the patterns of precipitation and alteration in the time of snowmelt leading to various modifications in the fundamental plant traits (Bartomeus et al., 2011). Such shifts affect both the vegetation and the pollinators as follows: 1) Plants: Modification of timing of flowering events, changes in reproductive investment and increased reproductive output, shifts in the functional and phylogenetic diversity, altered pollen and nectar quality and quantity, and interruption of pollination and pollen transfer networks (Burkle et al., 2013; Kudo & Cooper, 2019). 2) Pollinators: Adjustment in the timing of emergence, geographical rearrangements of both the location and the foraging, ecological niches, and the manner of species interactions (Goulson et al., 2015; Scaven & Rafferty, 2013).

Climate change is impacting the interactions between plants and insects, affecting biodiversity, altering species distribution, and reshaping ecological networks (Memmott et al., 2007). Insect pollination plays a vital role in maintaining ecosystem functionality, as many flowering plants rely on pollinators for seed production and reproductive success (Ollerton et al., 2011). These disruptions have significant global implications, impacting the reproductive success of approximately 85–90% of wild plants (Sage et al., 2025). Nectar and pollen, which serve as the primary food sources for pollinators due to their rich content of carbohydrates, amino acids, proteins, and lipids, are also affected by elevated temperatures. As a result, changes in the quality and quantity of nectar and pollen further threaten pollinator health and the ecosystems they support (Takkis et al., 2015).

Biodiversity Based strategies for pollinator conservation

The maintenance of agro-ecosystems is a fundamental strategy for pollinator conservation, with particular emphasis on the preservation of semi-natural habitats (Dainese et al., 2019). Such large and semi-natural grasslands, heathlands, scrubland, wildflower strips, and hedgerows, in addition to any patches of forests and woodlands, mass-flowering crops, and even harvests, are essential characteristics to provide food and shelter to a wide variety of pollinators (Garibaldi et al., 2021). Extensive and semi-natural grasslands work as continuous sources of nectar and pollen throughout the growing season and as such, they promote such foraging behaviors (Baude et al., 2016). To conserve such critical habitats, overgrazing should be curbed because it is these habitats that should be out in place to support the floral population (Travers et al., 2011). The Heathlands and scrublands can not only make available forage but can also be located at the right place to provide nesting sites especially in the early spring when oviposition could disrupt a pollinators life-cycle (Tschumi et al., 2016). In a similar way, crops with mass-flowering such as legumes and oilseed rape are valuable as important nutritional sources early in the growing season when other sources of flora may yet be lacking (Woodcock et al., 2016). Another 70 percent of wild bee species nest in the soil and thus they depend on soil riches in order to survive (Harmon-Threatt, 2020). To protect these species, deep tillage and excessive use of pesticides should be avoided as this aspect can greatly hinder the existence of bee diversity. Forest edge, meadows, grasslands and other open woodland areas create a diverse habitat to

Table 1: Effects of climate change on non-bees pollinators**.**

Non-bee pollinators	Climate Change Effects
Ant	Altered feeding behavior; disruption in communities, populations, and colony structure (Rodríguez-Segovia & Gavilánez-Endara, 2025).
Flies	Reduced longevity, fecundity, pupal weights and increased mortality rate (Lu & Wang, 2025).
Moth and Butterflies	Shift in geographic range, distribution, population abundance, and phonological events (Utku & Akyol, 2025).
Birds	Changes in breeding patterns and migratory behavior due to altered food availability (Menon, 2025).
Wasps	Decline in population size and shorten lifespan (Fooladi et al., 2025).

accommodate a variety of floral, nesting and overwintering sites of the pollinators (Kennedy et al., 2013). Preventing deforestation is critical not only to preserve pollinator species but also to maintain the ecological integrity of their habitats (Potts, Imperatriz Fonseca, et al., 2016). Urban green spaces can act as important fugitive for pollinators (Baldock et al., 2019). Community initiatives, such as maintaining orchards, planting native trees along roadsides, and creating flower-rich gardens, contribute to both pollinator conservation and urban environmental quality (Aronson et al., 2017).

Additionally, biodiversity-friendly practices like intercropping and organic farming are well-recognized methods for enhancing pollinator habitats and conserving overall ecosystem biodiversity (Tamburini et al., 2020). Government bodies particularly the Ministry of Agriculture and Rural Affairs and the Ministry of Ecology and Environment as well as non-governmental organizations (NGOs), are instrumental in supporting pollinator conservation. By working at the local level with farmers and communities, these institutions help safeguard natural habitats and promote sustainable land-use practices (Potts, Imperatriz-Fonseca, et al., 2016). By adopting practices such as reducing pesticide and agrochemical application, avoiding early mowing of grasslands, and implementing forest-friendly management, they can create more pollinator-friendly landscapes (Belsky & Joshi, 2019).

Aligning agricultural practices with Common Agricultural Policy (CAP) objectives can further enhance pollinator support systems, promoting sustainable farming while protecting ecosystem services (Albrecht et al., 2020). Farmers are very important in the conservation of pollinator. The five main criteria which can be used to conserve the farmland pollinators are:

Fig. 2: The five measures that can be used to conserve farmland pollinators.

Technological Innovations in Pollinator Monitoring and Management

Plants and pollinators are essential not only to the agricultural production worldwide but also to the enhancement of ecosystem health and beauty or aesthetics and, therefore, warrant a critical investigation into the interaction between them (Alberti et al., 2023). The observation of the interactions between the pollinators and the plants helps in the researchers to understand the climatic factors affecting the relationships which are temporal and spatial. Traditional pollinator monitoring schemes are usually identified by the high labor and time costs, as well as by a great number of resources allocated to them. Still, with the introduction of advanced technologies, including digital photography and smartphones, pollinator monitoring is getting more and more practical, efficient, and non-invasive. In particular, smartphones are more affordable, easier to use and to access, thus enabling both scholars and citizen scientists to collect meaningful field-based data (Chiranjeevi et al., 2023).

In cases where it is difficult to identify insects on site, they are taken to a laboratory to run them through a process that may involve techniques like DNA barcoding, Meta barcoding, and microscopic the identification methods. This methodology though effective is quite destructive in that to find one it involves the killing of so many insects which can be a threat to the biodiversity.

The image-based monitoring systems using the machine learning algorithms to detect pollinators by morphological traits are a sustainable alternative to the manual counts (Guri et al., 2024). The requirements of a pollinator monitoring camera to suit real-life application is its ability to capture fast-moving insects, ability to operate in high temperatures and humidity, maintain operation time of at least eight hours off the power supply, cost-effective and easy to maintain. Surveillance cameras, fixed lens cameras, time-lapse devices, Apple iPod Nano, programmable microcomputers, and other devices like the NVIDIA Jetson Nano, and systems like the Luxonis microcomputer cameras are increasingly being explored with the purpose of achieving this goal. These innovations are transforming pollinator research, enabling high-throughput, real-time data collection to support biodiversity conservation and sustainable agricultural practices (Khujamatov et al., 2025). Pollination services provided by pollinators are essential for global food production and contribute significantly to the economy, making them vital to both natural and agricultural ecosystems (Khalifa et al., 2021). In order to facilitate their preservation and optimal governance, sophisticated tracking methodologies including Radio-Frequency Identification (RFID), Synthetic Aperture Radar (SAR), and an array of antenna configurations have been utilized to evaluate the load-bearing capacities and physical attributes of pollinators, with a particular emphasis on honeybees (Alburaki et al., 2021).

This schematic representation delineates the advanced technologies and modeling methodologies employed for the proficient surveillance and administration of pollinators. The framework given in the fig 3 is a technologically advanced and integrated pollinator monitoring system with the aim to improve precision agriculture and facilitate the conservation of biodiversity (Nizamani et al., 2024). Its key component is the use of the Angle Sensitive Pixels (ASP) technology- special optical sensors, built to capture time and space at high resolution, and designed to track the complex flight paths of pollinators (Aarif KO et al., 2025). This first module includes conceptual design of the ASP system, the miniaturization of the flight recorder to be used in the field and the data digital calibration and modeling of sensor outputs. In combination they enable the production of detailed flight data providing a baseline data set against which downstream analysis and system optimization can then be made (Ratnayake et al., 2023). This framework, taking this base, then implements pollinator foraging simulations which use an orchard environment model and a honeybee motion model. Such simulations depend on a highly competent path-planning algorithm, bee-BIRRT (Bi-directional Rapidly-exploring Random Tree), which allows one to model not only efficient and realistic movement trajectories in agricultural landscapes but also to make them biologically realistic (Maraveas et al., 2023). This simulated habitat does not only increase ecological insights into the foraging habit but also aids in strategic planning of pollinator friendly cropping regime too. The framework also includes a component that deals with mapping of novel or unknown environments with the help of instrumental pollinators which is supported by the agent-based modeling approach. This part incorporates various sub-models that include environmental, pollinator and flight models as well as the image-processing techniques in detection of obstacles as well as the Bee-BIRRT algorithm in their adaptive navigation approach (Fasihi et al., 2025).

Many of the studies have also reported an extremely high decline in the abundance and the diversity of songbirds and insects (Tallamy & Shriver, 2021). To investigate the causes of this decline further by examining insects in closer detail, scrutiny and examination of insects is important, in the sense that it is efficient and ruthless (Hailay Gebremariam, 2024). Some more developed paradigms of learning, which are more commonly used in other areas of science, are just beginning to enter the field of entomology and deep learning is one of them (Høye et al., 2021). Together with computer vision, it gives some new opportunities to address the situation with the low number of insects on the planet (Høye et al., 2021). The deep learning models can perform bio-monitoring by enabling researchers to estimate the levels of abundance of insects, localize and classify species, inquire about their phenotypic characteristics, survey their biodiversity, as well as, quantify their biomass (Ntoko, 2020). The models that are developed with a specific target to analyze image data and differentiate between the species of insects based on their image appearance are the Convolutional Neural Networks (CNNs) (Hansen et al., 2020). Details such as cameras, radar systems, and microphones that are present in the sensor-based monitoring system are being used more and more by agricultural researchers to forecast the existence and count of benevolent insects (Kiobia et al., 2023). Vertical- looking radars (VLRs) and harmonic scanning radar are some of the radar technologies that have existed and further led to the development of knows additional understandings with regard to populations of both migratory and non- migratory insects. Whereas VLRs can produce minute level information over a small scale, the harmonics radars will mostly be used in the case where it is necessary to sense flyings insects at low altitudes of few hundred meters (Alberti et al., 2023). Bioacoustics has also proved helpful in the study of birds and mammals; this specialty is often used in entomology (Penar et al., 2020). Recently even the pseudo-acoustic optical sensors have been presented as a substitute to the normal acoustic sensors presenting a better signal to noise ratio and hence detection capability(Balla et al., 2020).

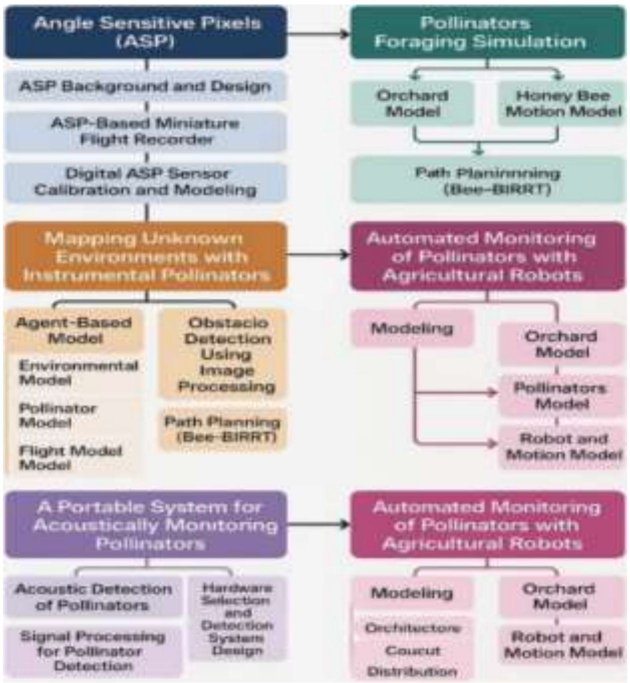

Fig. 3: Models and technologies of monitoring and management that are applied on the pollinators.

To transform sensor-collected data into biologically meaningful insights and to inspire new data collection strategies, deep learning is utilized extensively (Navulur & Prasad, 2017). These models are typically developed using open-source Python libraries and frameworks such as Tensor Flow, Keras, PyTorch, and Scikit-learn, which support robust and scalable solutions for insect monitoring (Géron, 2022).

Policy Dimensions for pollinator Conservation

Pollinators contribute significantly to the productivity of approximately 75% of globally important food crop species and play an essential role in sustaining terrestrial ecosystems. Nearly 90% of all flowering plants depend on animal pollination, making pollinator health fundamental not only to biodiversity but also to human well-being, nutrition, and economic stability (Porto et al., 2020). Despite growing scientific, public, and political attention, as well as numerous practical conservation efforts, pollinator populations continue to decline (Dicks et al., 2016). A review of current conservation initiatives reveals that further scientific understanding is needed in several critical areas, including the global status and trends of pollinator populations, the risks and co-benefits of conservation actions for ecosystems, the societal value of pollinator services, the development of practical and scalable solutions, and the complex interactions between the direct and indirect drivers of decline (Porto et al., 2020). Moreover, establishing integrated frameworks is vital to reversing these trends. Plants play a key role in shaping landscapes by regulating microclimates, preventing soil erosion, and serving as natural windbreaks functions that collectively support pollinator habitats and health (Porto et al., 2021). Wild pollinator conservation is valuable to the ecosystems as well as human society and the provided measures have an opportunity to turn the tide in population losses (Potts, Imperatriz-Fonseca, et al., 2016). Society also plays an active role in conservation through practices such as planting pollinator-friendly flowers, installing bee hotels, and engaging in responsible beekeeping (Aronson et al., 2017). However, reversing pollinator decline requires systemic changes in behavior and policy across all levels of governance, from individual landowners and local communities to national governments and multinational corporations (Porto et al., 2020). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) provides a comprehensive conceptual framework and global assessment that compiles evidence on the values, status, and trends of pollinators, along with the drivers, risks, and necessary responses to their decline (Hinsch et al., 2024). This framework considers a wide range of interconnected elements, including direct environmental drivers such as climate and weather patterns; the broader concept of nature, encompassing the biosphere, atmosphere, lithosphere, and hydrosphere; nature's contributions to people; human well-being and quality of life; anthropogenic assets such as infrastructure and technology; and institutional, governance, and indirect factors such as sociopolitical systems, economic activities, cultural values, and global trade. Together, these dimensions offer an integrated approach to understanding and addressing the complex challenge of pollinator conservation (Porto et al., 2020).

Challenges and Future Directions

Global baseline data on pollinator species composition and population dynamics remain limited, particularly in the Global South, where long-term ecological monitoring is scarce. The absence of comprehensive taxonomic records and behavioral datasets hampers accurate assessments of pollinator decline trajectories (Borregaard & Rahbek, 2010). Climate-induced shifts in the timing of flowering and pollinator emergence are increasingly leading to phonological mismatches, which reduce visitation rates and seed set in key crops such as tomato, avocado, coffee, and guava. These mismatches threaten agricultural productivity worldwide, especially in regions that rely heavily on pollination services (Gagic et al., 2015; Kudo & Cooper, 2019). Although emerging technologies such as IoT-based hive monitoring systems (e.g., HiveLink) and computer vision tools (e.g., YOLO-based models) offer advanced capabilities for tracking pollinator activity, their adoption is constrained by high costs, technical complexity, and inadequate digital infrastructure. These limitations are particularly acute in smallholder and resource-limited farming contexts (Jeong et al., 2024; Sharma et al., 2024).

Despite increased global awareness, current policy frameworks at both national and local levels are often fragmented and fail to holistically integrate ecological, technological, and socio-behavioral dimensions. Existing initiatives frequently overlook behavior-change theories that could foster community-led investment in pollinator habitats and the adoption of agro-ecological practices (Rivaroli et al.; Tolera & Ballantyne, 2021). Moreover, the continued use of harmful agrochemicals such as neonicotinoid insecticides and glyphosate remains a significant driver of pollinator mortality. Regulatory systems often underestimate the sub-lethal and cumulative impacts of these chemicals on both wild and managed pollinator populations (Bartling et al., 2024; Topping et al., 2024).

To address these gaps, it is critical to establish long-term, integrated monitoring platforms that combine edge computing, remote sensing, bioacoustics sensors, and citizen science initiatives to capture spatial and seasonal trends in pollinator activity (Artamendi et al., 2025; Ternar et al., 2025). Investment in taxonomic capacity building and the development of open-access biodiversity repositories is essential for closing data deficits (Goulson et al., 2015). Deploying species distribution models alongside phonological forecasting tools can help predict ecological mismatches, habitat shifts, and population declines (Rafferty, 2017; Xu et al., 2025). Integrating ecological modeling with crop yield simulations will support the design of proactive mitigation strategies and enable precision pollination management (Bosshard et al., 2025). To democratize pollinator surveillance, the promotion of low-cost sensor hubs, solar-powered smart hives, mobile-based monitoring platforms, and user-friendly computer vision applications is recommended. Open-source platforms such as YOLO-based recognition systems should be adapted to local insect taxa, languages, and field conditions to ensure broader accessibility and usability (Sapkota et al., 2024; Venverloo & Duarte, 2024).

To advance pollinator conservation within sustainable agriculture, it is imperative to develop cohesive policy packages that align the objectives of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the FAO's Climate-Smart Agriculture (CSA) framework, and national biodiversity strategies (Potts, Ngo, et al., 2016). These integrated policies should embed pollinator conservation within broader climate-smart and agro-ecological agendas. Adoption of pollinator-supportive practices can be incentivized through ecosystem service payment schemes, carbon credit mechanisms, and targeted subsidies linked to pollinator-friendly land use (Hanley et al., 2015; Murphy, 2022). Farmer- and community-led conservation must be prioritized through participatory programs such as pollinator gardens, bee hotels, hedgerow planting, and habitat restoration efforts. Applying insights from the social sciences is essential to effectively drive behavioral change among stakeholders. This includes leveraging locally relevant narratives, knowledge-sharing platforms, and culturally sensitive engagement strategies (Awazi, 2025; Galleli & Amaral, 2025).

To ensure interdisciplinary coherence, cross-sectorial consortia should be established to connect ecologists, agricultural engineers, agronomists, social scientists, and policymakers. Such collaborations should emphasize co-designed research initiatives that integrate the development of monitoring tools, agro-ecological interventions, and evaluation frameworks. These efforts must account for both ecological resilience and socioeconomic outcomes to ensure scalable and sustainable impact (Bie et al., 2025; Dainese et al., 2019).

Conclusion

Pollinators are foundational to global food security and ecosystem functioning, yet they are increasingly threatened by climate change, habitat degradation, and the widespread use of agrochemicals. This review underscores that the integration of biodiversity-based agricultural practices, advanced monitoring technologies, and Climate-Smart Agriculture (CSA) principles provides a viable, sustainable pathway for enhancing both pollinator conservation and agricultural productivity. Restoring habitat heterogeneity, promoting diversified agro-ecosystems, and minimizing pesticide dependency contribute significantly to strengthening ecological resilience. The deployment of artificial intelligence-driven tracking systems, IoT-enabled hive sensors, and computer vision technologies facilitates automated and precise pollinator monitoring, enabling data-informed, targeted interventions. Embedding these technological innovations within the CSA framework enhances resource efficiency and supports adaptive management under dynamic climatic conditions. Achieving meaningful outcomes will require closing critical research and data gaps through long-term monitoring, scaling technologies for accessibility among smallholder farmers, and aligning policy frameworks with behaviorally informed conservation strategies. Interdisciplinary collaboration among scientists, policymakers, farming communities, and other stakeholders is essential to this endeavor. Ultimately, climate-smart pollinator management represents more than a conservation goal it is a strategic imperative for safeguarding global food systems, preserving biodiversity, and supporting resilient livelihoods in the face of a changing climate.

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