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REVIEW PAPER

Ecosystem Services by Insect Pollinators, Their Crisis and Climate Change Effects

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ABSTRACT

Insects provide indispensable ecosystem services that sustain biodiversity, agricultural productivity, and ecological resilience. This literature explores the multifaceted roles of insects in ecosystem functioning, emphasizing pollination, decomposition, natural pest control, and aquatic ecosystem maintenance. Pollinators such as bees, butterflies, and flies contribute significantly to global food security and plant reproduction, while decomposer and predatory insects enhance soil fertility and pest regulation. The chapter highlights how insect diversity underpins ecosystem stability and how its decline poses severe risks to food systems and environmental health. It examines the growing threats from habitat loss, monoculture farming, pesticide overuse, climate change, and invasive species, which collectively disrupt ecological balance and diminish pollination efficiency. Additionally, it discusses the innovative potential of bio-inspiration derived from insect physiology and behavior in advancing sustainable technologies and climate adaptation. Current global initiatives, including those led by IPBES and FAO, are also reviewed for their efforts in promoting insect conservation and policy integration. The chapter concludes by emphasizing the urgent need for ecosystem-based management, landscape diversification, and strengthened institutional support to safeguard insect-mediated services essential for global sustainability, climate resilience, and human well-being.

HIGHLIGHTS

- Discussing critical ecological roles of insects in pollination, decomposition, pest control, and ecosystem maintenance.
- Exploring major threats to insect diversity from habitat loss, pesticides, climate change, and monoculture farming.
- Need for ecosystem-based management, conservation policies, and bio-inspired innovations for sustainability.

Keywords: Insects, ecosystem, farming, climate, biodiversity, Crisis

Ecosystem services are the direct and indirect benefits that humans derive from natural ecosystems, classified into provisioning, regulating, supporting, and cultural categories (MEA, 2005; Manasa *et al.* 2018; Mukesh *et al.* 2024). Biodiversity serves as the foundation of these services, as it ensures the stability, resilience, and productivity of ecological systems (Cardinale *et al.* 2012; Ray *et al.* 2025). Species diversity maintains ecosystem multifunctionality, including nutrient cycling, pollination, and pest regulation (IPBES, 2019; Krishna *et al.* 2024; Sarkar *et al.* 2024; Hemashree *et al.* 2025). The global

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concern over biodiversity loss has grown because of its potential to disrupt ecological processes and jeopardize food and water security (Zaman *et al.* 2017; Díaz *et al.* 2019; Maitra and Ray, 2019; Maitra *et al.* 2023a). Therefore, understanding biodiversity's role in sustaining ecosystem services is essential for developing conservation and climate-resilient management strategies (Fig. 1).

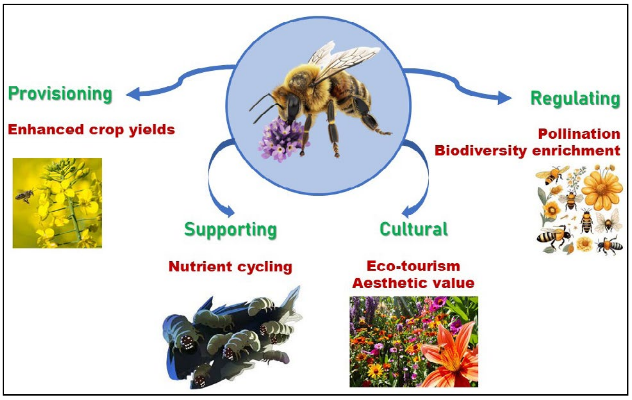

Fig. 1: Facilitating ecosystem services by insect pollinators

Insects play vital roles in maintaining ecological balance through services such as pollination, nutrient recycling, pest regulation, and decomposition (Losey and Vaughan, 2006; Maitra *et al.* 2018). Pollinators—mainly bees, butterflies, flies, beetles, and moths—are responsible for the sexual reproduction of over 75% of flowering plants and about 35% of global crop production (Klein *et al.* 2007; IPBES, 2016; Maitra *et al.* 2023b). These organisms contribute to ecosystem stability by ensuring plant diversity, food security, and genetic variability in crops (IPBES, 2019). Beyond pollination, decomposer insects like dung beetles, termites, and flies accelerate nutrient cycling and soil fertility (Maitra *et al.* 2001; Nichols *et al.* 2008), while predatory insects and parasitoids provide natural pest control by regulating herbivore populations (Roubik, 2018). Aquatic insects also maintain water quality and serve as bioindicators of freshwater ecosystem health (Brasil *et al.* 2022). The functional diversity of insects thus ensures the continuous flow of multiple ecosystem services critical for both natural and agricultural landscapes.

The diversity and abundance of insect species are closely linked to agricultural productivity and ecosystem resilience (Garibaldi *et al.* 2013; Zaman *et al.* 2017). Insect pollinators enhance fruit set, seed quality, and yield stability in over 70% of crop species globally (Klein *et al.* 2007). Wild pollinators, particularly native bees, often complement managed honeybees, increasing yield even under intensive farming systems (Garibaldi *et al.* 2020; Maheswari *et al.* 2025). Similarly, natural enemies such as lady beetles, parasitic wasps, and lacewings play a crucial role in biological pest suppression, reducing the dependency on chemical pesticides (Vanbergen *et al.* 2018; Ray *et al.* 2024). The decline in insect diversity, driven by habitat loss, pesticide use, and climate stress, has been associated with yield variability and decreased nutritional quality of crops (Hallmann *et al.* 2017; Wagner *et al.* 2021; Gitari *et al.* 2024). Thus, conserving insect biodiversity is not only an ecological necessity but also an economic imperative for sustainable agriculture.

Globally, the economic value of pollination services provided by insects is estimated to range between USD 235–577 billion annually (Lautenbach *et al.* 2012; IPBES, 2019). These services are particularly critical in tropical and subtropical regions where insect-pollinated crops such as coffee, cocoa, and fruits form the backbone of agricultural economies (Dicks *et al.* 2021). In South Asia and Sub-Saharan Africa, pollinator diversity directly influences food and nutritional security, especially for smallholder farmers reliant on pollinator-dependent crops (Aizen *et al.* 2009). However, long-term studies indicate a significant decline in global insect biomass—over 70% in some monitored areas—due to climate change, land-use conversion, and agrochemical exposure (Hallmann *et al.* 2017; Santosh *et al.* 2024). This decline poses severe risks to regional economies and ecosystem stability, underlining the need for integrated conservation and climate adaptation strategies that safeguard insect-mediated ecosystem services (Maitra and Zaman, 2017; Gaikwad *et al.* 2022; Maitra *et al.* 2024).

Ecosystem Services

Ecosystem services are the benefits people obtain from nature, spanning material goods (food, fibre, water) and non-material flows (climate regulation, nutrient cycling, cultural values) that sustain human societies and economies (Reid, 2006; IPBES, 2019; Sairam *et al.* 2025). Insects — and pollinators in particular — underpin many of these services by mediating processes such as pollination, decomposition and biological pest control; the integrity of these services is therefore tightly linked to insect biodiversity and ecosystem health (Das *et al*. 2021).

Definition and classification

Ecosystem services are commonly classified into four broad categories: provisioning services (products obtained from ecosystems, e.g., food, fibre, fresh water), regulating services (benefits from regulation of ecosystem processes, e.g., pollination, pest control, climate regulation), supporting services (fundamental ecological processes such as nutrient cycling and soil formation that enable other services), and cultural services (non-material benefits such as recreation, spiritual values and aesthetic inspiration). This typology helps link ecological functions to human well-being and policy, while recognizing that many services overlap (e.g., erosion control can be both supporting and regulating depending on time scale).

Importance of ecosystem services for human well-being

Ecosystem services provide the material basis for food, livelihoods, health and cultural identity; disruptions to these services therefore produce direct socio-economic impacts (IPBES 2019). Regulating services like pollination and natural pest control contribute to crop yields and quality, supporting local economies and nutritional security (Garibaldi *et al*. 2013; Gallai *et al*. 2009). Supporting services such as nutrient cycling maintain soil fertility over the long term, while cultural services sustain recreation, tourism and cultural heritage that have both intrinsic and economic value. The IPBES global assessment highlights that declines in biodiversity and ecosystem condition compromise service delivery and increase risks to human well-being worldwide (IPBES 2019).

Frameworks for assessing ecosystem services

Two cornerstone frameworks guide assessment and policy integration of ecosystem services. The Millennium Ecosystem Assessment (Reid, 2006) popularized the four-category service typology and demonstrated links between ecosystem change and human welfare, providing the conceptual basis for many subsequent studies. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has since extended and operationalized these ideas at global and regional scales, producing integrative assessments that quantify the state of nature, drivers of change, and policy options for conserving nature's contributions to people (IPBES 2019). These frameworks also emphasize plural values (ecological, economic and cultural) and encourage use of interdisciplinary methods (ecological monitoring, economic valuation, participatory approaches) to inform decisions.

Insects as key providers of regulating and supporting services

Insects are foundational providers of many regulating and supporting services. Pollinators (bees, flies, butterflies, beetles and others) ensure reproduction of a large proportion of wild and crop plants, directly influencing yields and trait quality (Klein *et al*. 2007; Garibaldi *et al*. 2013). Decomposer insects (e.g., dung beetles, termites, carrion-feeding flies) accelerate organic matter breakdown and nutrient recycling, increasing soil fertility and ecosystem productivity (Nicholsand Gardner, 2011; Maitra *et al*. 2025a,b). Predatory and parasitoid insects afford natural pest suppression that reduces crop losses and the need for chemical control (Losey and Vaughan, 2006). Aquatic insects contribute to water purification and biogeochemical cycling in freshwater systems and serve as sensitive indicators of water quality (Brito *et al*. 2024). Because insects are both species-rich and functionally diverse, their declines can rapidly degrade multiple ecosystem processes simultaneously.

Economic valuation of insect-mediated ecosystem services

Valuing insect services helps make their contributions visible to decision-makers and can motivate conservation and land-use policy. Early global estimates placed the annual value of insect pollination in the order of hundreds of billions of euros/dollars (Gallai *et al*. 2009; Lautenbach *et al*. 2012; Nungula *et al*. 2023), and national/regional assessments continue to show substantial contributions of pollination to agricultural revenue and nutrition (Khalifa *et al*. 2021). In the United States and other countries, aggregated valuations of insect services (pollination + pest control + decomposition) indicate multi-billion dollar benefits annually (Loseyand Vaughan 2006). While valuation methods vary (market price, replacement cost, avoided damage, ecosystem-service accounting), they consistently indicate that declines in insects would produce large economic losses and threaten food and nutritional security, especially in regions depending on pollinator-dependent crops.

Role of Insects in Ecosystem Services

Insects are among the most diverse and functionally important groups in the biosphere, performing a wide range of ecological roles that sustain ecosystem functioning and human well-being (Loseyand Vaughan, 2006). They contribute to essential ecosystem services such as pollination, decomposition, nutrient cycling, pest regulation, and soil formation (IPBES, 2019). Their adaptability, ecological plasticity, and vast species richness enable them to occupy nearly every terrestrial and freshwater habitat, making them integral to the stability and productivity of both natural and agricultural ecosystems (Wagner *et al.* 2021). Understanding their roles in ecological processes is vital for biodiversity conservation and the long-term sustainability of ecosystem services under changing environmental conditions (Cardinale *et al.* 2012).

Functional Diversity of Insects and Ecosystem Stability

Functional diversity—the variety of biological traits and ecological functions that species exhibit—is a key determinant of ecosystem stability (Tilman *et al.* 2014). Insects demonstrate extraordinary functional diversity, encompassing pollinators, decomposers, herbivores, predators, and parasitoids that collectively sustain essential ecosystem processes (Nichols *et al.* 2013). For example, bees, flies, beetles, and butterflies are indispensable pollinators of more than 75% of flowering plant species, while detritivorous insects like dung beetles and termites decompose organic matter, improving soil structure and nutrient cycling (Klein *et al.* 2007; Nichols *et al.* 2013). Predatory insects such as lady beetles, lacewings, and wasps regulate pest populations, maintaining ecological balance. High functional redundancy—where multiple insect species perform similar ecological roles—provides resilience against environmental stress, ensuring that ecosystem functions continue even when certain species decline (Cardinale *et al.* 2012). Thus, insect functional diversity underpins ecosystem multifunctionality and long-term ecological stability.

Trophic Interactions and Ecological Balance

Insects occupy nearly every trophic level, forming intricate food webs that maintain ecological balance and energy flow (Bohan *et al.* 2017). As primary consumers, herbivorous insects such as caterpillars, aphids, and leaf miners convert plant biomass into food resources for higher trophic levels, supporting birds, amphibians, and mammals (Hallmann *et al.* 2017). Predatory and parasitic insects, in turn, regulate populations of herbivorous pests, preventing ecosystem degradation and crop losses (Vanbergen *et al.* 2020). Detritivorous insects recycle nutrients by breaking down decaying plant and animal matter, facilitating microbial decomposition and soil fertility. These trophic interactions maintain ecological equilibrium, with disruptions—such as pesticide overuse or climate-driven phenological mismatches—leading to cascading effects on ecosystem functioning (Wagner *et al.* 2021). Hence, preserving trophic diversity among insects is essential for sustaining ecosystem resilience and productivity.

Insect Biodiversity as an Indicator of Ecosystem Health

Insect biodiversity serves as a sensitive and reliable indicator of ecosystem health and environmental change (Brito *et al.* 2024). Because insects respond rapidly to alterations in habitat quality, climate, and resource availability, changes in their abundance or community composition can reflect broader ecosystem disturbances. For instance, declines in pollinator diversity indicate habitat fragmentation and pesticide contamination, while reductions in aquatic insect populations reveal water pollution and eutrophication (Nanda *et al.* 2010; Mohanty *et al.* 2016; Hallmann *et al.* 2017; Sahu *et al.* 2024). Monitoring insect biodiversity thus provides early warning signals for ecosystem degradation, enabling targeted conservation interventions. Moreover, maintaining high insect diversity supports ecosystem functions that contribute to climate resilience, soil fertility, and crop production (IPBES, 2019). Therefore, insects act both as functional agents of ecosystem services and as diagnostic indicators of environmental integrity.

Case Studies on Insect Contributions to Ecosystem Processes

Numerous studies worldwide illustrate the critical roles insects play in sustaining ecosystem services. In agricultural landscapes, wild pollinators have been shown to enhance fruit set and yield stability across diverse crops, independent of managed honeybee abundance (Garibaldi *et al.* 2013). In tropical forests, dung beetles significantly improve soil aeration and nutrient cycling, supporting forest regeneration and carbon sequestration (Nichols *et al.* 2008). Similarly, aquatic insects such as mayflies and caddisflies serve as bioindicators of freshwater quality, helping detect early signs of ecological degradation (Brito *et al.* 2024). In natural pest control, parasitic wasps and predatory beetles have successfully reduced pest outbreaks in both organic and conventional farming systems (Vanbergen *et al.* 2018). These examples collectively underscore the indispensable role of insects in maintaining ecosystem processes that sustain both biodiversity and human well-being.

Pollination

Pollination is one of the most vital ecosystem services provided by insects and other animals, underpinning global biodiversity, food production, and ecosystem stability. It facilitates the sexual reproduction of flowering plants, ensuring genetic diversity and the formation of fruits and seeds essential for both wild ecosystems and agricultural systems (Potts *et al.* 2016). Insect pollinators, including bees, butterflies, flies, beetles, and moths, play a central role in maintaining this ecological process, contributing directly to global food security and indirectly to climate resilience and habitat sustainability (Klein *et al.* 2007; Dicks *et al.* 2021).

Definition and Ecological Importance of Pollination

Pollination is the process by which pollen grains are transferred from the anther (male organ) of a flower to the stigma (female organ), enabling fertilization and seed production (Ollerton *et al.* 2011). It is a cornerstone of terrestrial biodiversity, with approximately 87.5% of flowering plant species depending, at least partially, on animal-mediated pollination. The ecological importance of pollination extends beyond plant reproduction—it supports food webs, provides habitats, and sustains ecosystem resilience by ensuring plant genetic diversity and adaptive capacity (IPBES, 2016). Furthermore, pollination contributes to soil stabilization, carbon sequestration, and water regulation through the maintenance of vegetative cover and ecosystem integrity (Garibaldi *et al.* 2013). The loss or decline of pollinators can therefore trigger cascading effects throughout ecosystems, reducing biodiversity and threatening human well-being (IPBES, 2019).

Types of Pollinators

Pollinators are taxonomically diverse, including insects, birds, bats, and even small mammals, but insects—particularly bees—are the most significant contributors (Klein *et al.* 2007).

Bees (honeybees, bumblebees, solitary bees) are the most efficient pollinators due to their morphological adaptations such as branched body hairs and specialized pollen-carrying structures.

Butterflies and moths contribute to long-distance pollination, particularly in wildflower and forest ecosystems, often visiting tubular and brightly colored flowers.

Flies (syrphid flies and bee flies) are vital in colder or high-altitude environments where bees are less active.

Beetles, known as “mess-and-soil” pollinators, play a major role in pollinating basal angiosperms such as magnolias and water lilies.

Other groups, including **wasps**, **thrips**, and **ants**, also contribute to specific pollination systems.

This diversity of pollinator taxa ensures functional redundancy, buffering ecosystems against environmental perturbations and pollinator declines (Dicks *et al.* 2021).

Pollination Mechanisms and Plant–Pollinator Interactions

Pollination mechanisms are shaped by co-evolutionary relationships between plants and their pollinators (Ollerton *et al.* 2011). Floral morphology, color, scent, and nectar composition have evolved to attract specific pollinator guilds, leading to intricate plant–pollinator networks that enhance ecological specialization and stability. For example, tubular flowers with deep corollas are typically pollinated by long-tongued bees or butterflies, while open, radial flowers attract a wider range of insects. These interactions are mutualistic—pollinators obtain nectar or pollen as a food source, while plants achieve fertilization and reproductive success. However, anthropogenic pressures such as habitat loss, pesticide use, and climate change disrupt these interactions, leading to "phenological mismatches" where flowering times no longer align with pollinator activity (Settele *et al*. 2016). Such disruptions can reduce pollination efficiency, affect plant reproductive success, and alter community composition, thereby threatening ecosystem resilience (Wagner *et al*. 2021).

Pollination Services in Natural and Agricultural Ecosystems

Pollination supports both natural ecosystems and agricultural productivity. In natural ecosystems, pollination maintains floral diversity, supports wildlife food chains, and aids forest regeneration (Potts *et al*. 2016). In agriculture, approximately 35% of global crop production depends on pollinators, including fruits, vegetables, oilseeds, nuts, and legumes (Klein *et al*. 2007). Crops such as almonds, apples, coffee, and rapeseed are particularly reliant on insect pollination (Garibaldi *et al*. 2013).

The economic value of pollination services is immense—estimated at over USD 235–577 billion annually (IPBES, 2019). Beyond yield quantity, pollinators enhance crop quality, uniformity, and shelf life (Dicks *et al*. 2021). Yet, widespread pollinator declines, driven by pesticide exposure, habitat loss, and climate change, threaten these services globally. Sustainable management strategies such as creating pollinator habitats, promoting floral diversity, and reducing agrochemical inputs are thus essential to safeguard pollination services and ensure long-term agricultural resilience.

Economic and Nutritional Value of Pollination Services

Pollination delivers enormous economic value by increasing crop yields, improving product quality (size, uniformity, shelf-life) and enabling the production of nutrient-rich foods (fruits, vegetables, nuts) that are important for human diets (Gallai *et al*. 2009; IPBES, 2019). Global monetary estimates of animal pollination vary with method and scope: commonly cited ranges are roughly USD 235–577 billion per year for contributions to global crop production (Lautenbach *et al*. 2012; IPBES, 2019), while some analyses and recent re-estimates place short-term or broader service values closer to ~USD 1 trillion or more depending on assumptions about crop dependence and valuation method (Gebremedhn *et al*. 2025). Importantly, the economic value underestimates the *nutritional* role of pollinators: many pollinator-dependent crops provide vitamins, micronutrients and dietary diversity that support human health. Regional valuations illustrate this: for example, pollination services in Nepal were conservatively estimated at ~US$477 million annually and accounted for a substantial share of agricultural revenue and micronutrient supply. Thus, pollinator loss carries both direct market impacts (reduced yields, higher production costs) and non-market nutritional costs (reduced access to nutrient-dense foods), disproportionately affecting smallholders and vulnerable populations (IPBES, 2019; Devkota *et al*. 2024).

Decline in Pollinator Diversity and Abundance

A growing body of monitoring, long-term experiments and meta-analyses documents declines in insect and pollinator abundance, richness and biomass across many regions and taxa (Hallmann *et al*. 2017; Wagner *et al*. 2021). Long-term data show dramatic reductions in flying insect biomass in some European sites (Hallmann *et al*. 2017) and widespread downward trends in multiple pollinator groups reported in reviews and national surveys. Drivers are multiple and interacting: habitat loss and fragmentation, intensive agricultural practices (including high fertilizer and pesticide inputs), floral resource depletion, invasive species, pathogens, and climate change all contribute (Durgude *et al*. 2022; Santosh *et al*. 2023). Recent field studies and experimental evidence (e.g., long-running grassland experiments) have highlighted the negative effects of heavy fertilizer use and reduced floral diversity on pollinator numbers (Balfour *et al*. 2025). The declines show spatial heterogeneity—some regions/species fare worse than others—but the overall pattern signals increased vulnerability of pollination services, with knock-on effects on plant reproduction and food production (Lee *et al*. 2024; IPBES, 2019).

Climate Change Impacts on Pollination Phenology and Efficiency

Climate change affects pollination through multiple pathways: shifts in phenology (timing of flowering and pollinator activity), range shifts of both plants and pollinators, altered behavior and physiology of pollinators, and changes in community composition and interaction networks (Settele *et al*. 2016). Phenological shifts are often asynchronous: plants and their pollinators respond at different rates to warming and altered precipitation, producing phenological mismatches that reduce temporal overlap and pollination efficiency. Experimental and modeling studies indicate that mismatches can reduce seed set and plant fitness and may increase pollen limitation, especially for specialized plant–pollinator pairs (Lee *et al*. 2024). Warming can also expand some pollinators' ranges poleward or to higher elevations while contracting others, changing community composition and potential pollination outcomes (Settele *et al*. 2016). Furthermore, extreme weather events (late frosts, heavy rains, droughts) can disproportionately affect pollinator life stages (e.g., queen survival in bumblebees) and lead to year-to-year variability in pollination services.

Conservation and Management Strategies for Pollinators

Sustaining pollination requires integrated, multi-scale strategies that address threats to habitat, food resources, and exposure to agrochemicals while promoting resilient landscapes and supportive policy frameworks (Pires and Maués, 2020). Key approaches supported by recent guidance and evidence include:

Habitat protection and restoration: conserve and restore semi-natural habitats, hedgerows, field margins and wildflower strips to provide nesting sites and continuous floral resources across seasons.

Agri-environment and ecological intensification: promote crop diversification, cover cropping, reduced tillage and landscape heterogeneity to increase wild pollinator abundance and resilience (Chappa *et al*. 2022).

Pesticide risk reduction and integrated pest management (IPM): minimize prophylactic insecticide use, implement best management practices (timing, targeted application), adopt non-chemical controls, and use managed pollinator protection plans.

Nutritional and nesting resource planning: design floral calendars and nesting habitat (bare ground, stems, cavities) to ensure continuous resources for bees and other pollinators throughout the season.

Monitoring and adaptive management: implement standardized monitoring (both citizen science and professional surveys) to detect trends, inform local actions, and evaluate effectiveness of interventions.

Policy instruments and incentives: use payments for ecosystem services, agri-environment schemes, and regulatory measures to incentivize pollinator-friendly practices and integrate pollinator needs into land-use planning.

Ex situ and managed pollinator strategies (carefully targeted): where appropriate, managed bees (*Apis* spp., *Bombus* spp.) can supplement services but must be used cautiously to avoid disease spillover and competition with wild pollinators.

Public engagement and cross-sector partnerships: engage farmers, communities, industry and research institutions through extension, certification schemes, and public–private partnerships to scale best practices.

Evidence indicates that *combinations* of practices at field and landscape scales—rather than single interventions—produce the most reliable gains in pollinator diversity and pollination services (Garibaldi *et al*. 2013; IPBES, 2019). Effective conservation also requires addressing broader drivers (land-use change, climate mitigation) and tailoring interventions to local ecological and socio-economic contexts.

Decomposition of organic matter

Decomposition is a core ecosystem process in which dead organic matter is broken down into simpler compounds, releasing nutrients that sustain primary production and soil fertility. Insects (and other soil fauna) accelerate physical fragmentation, enhance microbial access to substrates, and convert organic residues into forms readily taken up by plants; therefore, they are indispensable agents of nutrient recycling and ecosystem functioning (Roh *et al*. 2024).

Role of insects in decomposition processes

A wide range of insect taxa are active decomposers across ecosystems. Detritivores such as dung beetles, carrion-feeding flies, and many coleopteran larvae fragment and consume coarse organic material, accelerating the exposure of litter to microbial decomposers. Termites and wood-boring beetles are especially important in woody and arid systems where they break down lignified tissues and transfer carbon and nutrients from dead wood into the soil food web (Roh *et al*. 2024). In aquatic systems, insect larvae (e.g., caddisflies, stoneflies) shred leaf litter and increase surface area for microbial decomposition, linking terrestrial inputs to stream productivity. In many systems, the physical processing by insects (chewing, tunnelling, burying) both increases decomposition rates and modifies the pathways of nutrient return (Palmer *et al*. 2025).

Contribution to nutrient cycling and soil fertility

By breaking down plant and animal residues, insects speed the release and redistribution of nitrogen, phosphorus and other key elements, making them available for plant uptake (Perveen *et al*. 2025). Dung-processing insects, for example, bury and homogenize dung, increasing soil aeration, improving microbial activity, and transferring a high-quality nutrient pulse into soils that boosts pasture productivity. Insect-derived products such as frass (excreta) and decomposer cadavers are themselves nutrient-rich inputs that can stimulate microbial decomposition and improve soil structure; recent applied research also documents beneficial effects of insect frass amendments on crop growth and nutrient uptake (Hwang *et al*. 2022). Through these actions insects help maintain soil organic matter turnover, aggregate stability and the biogeochemical cycles that underpin long-term soil fertility (Palmer *et al*. 2025).

Relationship between decomposer communities and ecosystem productivity

Ecosystem productivity often reflects the composition and functional breadth of decomposer communities. Experimental and field studies show that higher diversity and functional complementarity among decomposers (macrofauna + microbes) commonly increase decomposition rates and nutrient availability, supporting greater plant growth and resilience to stress. Conversely, loss or simplification of decomposer assemblages can slow nutrient turnover, produce nutrient bottlenecks, and reduce primary productivity—effects that cascade through food webs (Palmer *et al*. 2025). Some work also highlights context dependency: the identity of dominant decomposers (e.g., termites vs. beetles) and abiotic conditions (moisture, temperature) determine whether decomposition accelerates or becomes limited, so community composition matters as much as total abundance (Roh *et al*. 2024).

Influence of climate factors on decomposition rates

Temperature, moisture and extreme weather events strongly modulate decomposition, both directly (via metabolic-rate effects on insects and microbes) and indirectly (via changes in community composition and plant litter quality). Warming typically increases metabolic and microbial activity and can speed decomposition up to a point, but droughts, altered precipitation regimes and low-flow conditions in streams often reduce detritivore activity and slow litter breakdown. Climate change can also alter the relative importance of insects versus microbes in decomposition—for instance, larger arthropods (termites, beetles) may become more or less important depending on regional drying or warming trends. Importantly, climate-driven shifts in phenology and abundance of decomposer insects can decouple timing of nutrient release from plant demand, with implications for productivity and carbon dynamics (Palmer *et al*. 2025).

Impacts of pesticide use and habitat loss on decomposer diversity

Anthropogenic land-use change and agrochemical inputs have pronounced negative impacts on decomposer insects. Broad-spectrum insecticides, repeated applications and systemic compounds reduce abundance and diversity of dung beetles, carrion feeders, soil fauna and non-target flies and beetles, thereby slowing decomposition and disrupting nutrient flows. Habitat loss and homogenization reduce resource continuity (dung, woody debris, leaf litter), fragmenting decomposer communities and lowering functional redundancy—making decomposition processes less resilient to perturbation. Recent monitoring and experimental studies report cases where pesticide-driven declines in beetles led to higher fly abundance and altered pathogen dynamics, illustrating how perturbing decomposer guilds can produce unexpected ecological consequences. Mitigating these impacts requires reducing harmful pesticide use, restoring habitat heterogeneity and maintaining resource inputs that sustain decomposer assemblages.

Natural Pest Management

Natural pest control (biological control) is the regulation of pest populations by living organisms — predators, parasitoids and pathogens — and is a cornerstone of sustainable agroecosystems. By reducing pest densities and suppressing outbreaks, natural enemies lower reliance on chemical pesticides, stabilize yields, and help maintain ecosystem health and biodiversity.

Concept and ecological basis of biological pest regulation

Biological pest regulation rests on ecological principles: density-dependent predation/parasitism, trophic cascades, and the context-dependent strength of species interactions (Sentis *et al*. 2022). Natural enemies reduce pest population growth either directly (consumption, parasitism, infection) or indirectly (inducing behavioural changes that lower pest feeding or reproduction) — the latter often called "enemy-risk" or non-consumptive effects and can be as important as direct mortality in suppressing pests. The effectiveness of biological control depends on landscape context (availability of refuges and alternative prey), temporal complementarity between enemies and pests, and the functional traits of both pests and enemies (e.g., searching efficiency, reproductive rate). Conservation biological control — managing habitats and practices to favor resident natural enemies — and classical, augmentative or inundated releases (introducing natural enemies) are the three main applied strategies that derive from these ecological foundations (Wyckhuys, 2025).

Key insect natural enemies: predators, parasitoids, and pathogens

Predators: Generalist and specialist predators (lady beetles, lacewings, spiders, ground beetles, predatory hemipterans) consume multiple pest life stages and can provide immediate suppression in many cropping systems. Their broad diet often makes them resilient to fluctuations in single-prey populations, but they can be vulnerable to pesticides and habitat simplification.

Parasitoids: Hymenopteran and dipteran parasitoids lay eggs in or on host insects; their larvae develop by consuming the host, often causing host death. Parasitoids (e.g., *Trichogramma, Aphidius, Tamarixia*) are highly specific and have been successfully used in classical and augmentative biological control programs against lepidopteran, hemipteran and psyllid pests.

Pathogens (entomopathogens): Bacteria (*Bacillus thuringiensis*), fungi (*Beauveria, Metarhizium*), viruses (nucleopolyhedro viruses) and nematodes infect and kill pests; they are used as biopesticides in augmentative strategies and can integrate well with conservation approaches but require careful deployment to avoid non-target impacts and interactions with other natural enemies. Collectively these groups create multi-layered pest suppression: predators and pathogens reduce pest abundance quickly, while parasitoids and long-term community dynamics maintain lower baseline populations (Sentis *et al*. 2022).

Examples of successful natural pest control systems

There are numerous documented successes across classical, augmentative and conservation biological control:

Classical biological control: Introduction of specialized parasitoids to control invasive pests (e.g., *Tamarixiadryi* against *Tamarixia*-associated psyllids in specific regions) has led to long-term suppression without continuous inputs.

Augmentative control: Periodic releases of predators/parasitoids (e.g., *Trichogramma* spp. against lepidopteran eggs, inundated fungal sprays) have been effective in greenhouses and certain field crops when timed to pest phenology.

Conservation biological control: Landscape diversification (hedgerows, flower strips, non-crop refuges) and reduced insecticide use have increased natural enemy abundance and lowered pest pressure in vineyards, cereals and rice systems, improving yields and lowering input costs. Meta-analyses and landscape studies show that heterogenous landscapes and lower pesticide intensity generally increase predation rates and reduce crop losses (Wyckhuys, 2025). These successes demonstrate that ecological knowledge combined with appropriate management can translate into reliable pest suppression at field and landscape scales.

Disruption of pest control due to landscape changes and pesticide overuse

Agricultural intensification, habitat loss and simplification reduce resource and refuge availability for natural enemies, breaking the ecological linkages required for effective control (Mansier and van Rijn, 2024). Large monocultures and removal of non-crop habitats decrease enemy diversity and temporal continuity of resources (nectar, pollen, alternative prey), making pest outbreaks more likely. Simultaneously, broad-spectrum insecticides kill beneficials or impair their behaviour and reproduction; sublethal effects (reduced foraging, navigation, immune function) further compromise biocontrol. Pesticide drift can also degrade semi-natural habitats adjacent to fields, reducing landscape-scale control services. The combined effect is a vicious cycle: greater pesticide use reduces natural enemies, which increases pest pressure, prompting further chemical interventions (Wyckhuys, 2025).

Climate change impacts on predator–prey dynamics

Climate change alters the tempo and spatial dynamics of biological control in several ways. Warming shifts phenology (earlier emergence or multiple generations) of pests and their enemies, potentially creating temporal mismatches where enemies are out of phase with peak pest vulnerability (Sentis *et al*. 2022). Range shifts and differential physiological responses can change community composition — some natural enemies may expand poleward while others contract, altering local control capacity. Extreme events (droughts, floods, heat waves) can disproportionately affect higher trophic levels or interrupt overwintering stages of parasitoids, reducing their annual effectiveness (Wyckhuys, 2025). Climate-driven changes in plant nutritional quality or secondary chemistry can modify pest performance and susceptibility to enemies, with complex, context-dependent outcomes. Modeling and empirical studies indicate that climate change increases uncertainty in natural pest control and will require adaptive, resilient management strategies.

Integrating insect-based pest control in sustainable agriculture

Integrating biological control into sustainable systems requires combining landscape-scale habitat management, farm-level practices, and policy incentives:

Landscape and habitat actions: create and manage flower strips, hedgerows, cover crops and grassy margins to provide nectar, pollen and overwintering sites for natural enemies.

Crop and field practices: adopt crop rotations, intercropping, reduced tillage and synchronous planting to disrupt pest life cycles and support enemy populations.

Pesticide stewardship: prioritize selective products, apply pesticides only when thresholds are exceeded, use targeted timing to spare natural enemies, and adopt integrated pest management (IPM) protocols.

Augmentation and biological inputs: where necessary, carefully timed releases of biocontrol agents (predators, parasitoids, entomopathogens) can be paired with conservation measures; risk assessment and monitoring are essential to avoid non-target effects.

Monitoring, thresholds and decision support: use regular scouting, trap networks and threshold-based action to reduce prophylactic spraying and to evaluate biocontrol efficacy.

Policy and incentives: payments for ecosystem services, agri-environment schemes, extension support and supply-chain incentives (certifications) help scale adoption of biocontrol practices.

When combined, these actions can reduce chemical inputs, increase resilience to pests (including under climate variability), and deliver co-benefits for biodiversity, pollination and other ecosystem services.

Aquatic Insects

Aquatic insects, including groups such as *Ephemeroptera*, *Plecoptera*, *Trichoptera*, *Diptera*, *Coleoptera*, and *Hemiptera*, are among the most ecologically significant taxa in freshwater ecosystems. They contribute substantially to ecosystem functioning by mediating energy flow, processing organic matter, and linking aquatic and terrestrial food webs (Bonacina *et al*. 2023). These insects not only sustain aquatic biodiversity but also influence water quality and ecosystem resilience, making them valuable indicators of environmental change (Chakravarty and Gupta, 2024).

Diversity and Ecological Roles of Aquatic Insects

Aquatic insects display remarkable diversity and occupy a broad range of ecological niches — from grazers and shredders to predators and scavengers — depending on species and life stage. For example, may fly larvae graze on algae, caddisflies act as shredders of detritus, and dragonfly nymphs serve as apex predators in freshwater systems. Their life cycles often link aquatic and terrestrial environments, as adult emergence transfers energy and nutrients to terrestrial food webs. Such trophic versatility contributes to energy transfer and community stability, making aquatic insects vital to freshwater food webs and biogeochemical processes (Bonacina *et al*. 2023).

Functions in Nutrient Cycling and Water Purification

Aquatic insects enhance nutrient cycling by breaking down organic matter and facilitating microbial activity. Shredders and collector-gatherers convert coarse detritus into fine particulate organic matter, which accelerates mineralization and nutrient release. Grazing taxa, such as chironomids and some beetles, regulate periphyton biomass and promote primary production. Burrowing insects increase sediment oxygenation and improve nutrient exchange between sediment and water columns, thereby contributing to self-purification and improved water quality. These ecological processes play a central role in maintaining freshwater ecosystem productivity and resilience (Chakravarty and Gupta, 2024).

Indicator Role in Assessing Water Quality and Ecosystem Health

Because of their sensitivity to environmental change, aquatic insects are widely used as bioindicators of water quality (Persaud *et al*. 2022). The presence or absence of sensitive taxa, particularly *Ephemeroptera*, *Plecoptera*, and *Trichoptera* (the EPT index), provides reliable information about oxygen availability, organic pollution, and habitat integrity (Chakravarty and Gupta, 2024). Multi-metric indices like BMWP (Biological Monitoring Working Party) and ASPT (Average Score Per Taxon) have been developed globally based on macroinvertebrate composition to monitor ecological health. Long-term monitoring programs highlight that insect community structure integrates both chronic pollution and habitat modification, offering a powerful tool for evaluating ecosystem condition (Tampo *et al*. 2021).

Effects of Temperature Rise and Hydrological Alterations on Aquatic Insect Communities

Climate change exerts profound effects on aquatic insect assemblages by altering temperature regimes, flow dynamics, and oxygen availability (Johnson *et al*. 2024). Elevated water temperatures accelerate insect metabolism and development, potentially leading to changes in voltinism (number of generations per year) and species distributions. Cold-adapted taxa, such as many stoneflies and mayflies, are particularly vulnerable to warming and often decline as thermophilic species expand. Hydrological alterations — including droughts, floods, and altered flow regimes — disrupt larval habitats, reduce refugia, and increase mortality (Tampo *et al*. 2021). These disturbances not only reduce species richness but also affect functional diversity and weaken ecosystem services such as decomposition and nutrient cycling (Johnson *et al*. 2024).

Conservation Needs for Freshwater Insect Biodiversity

Conserving aquatic insect diversity requires an integrated watershed-based approach focusing on habitat quality, hydrological connectivity, and pollution control. Restoration of riparian vegetation, maintenance of environmental flow regimes, and reduction of nutrient and pesticide runoff are key to sustaining healthy insect communities. Conservation strategies should also emphasize climate adaptation, such as preserving cold-water refugia and enhancing habitat heterogeneity (Johnson, 2024). Moreover, integrating citizen science with professional biomonitoring can strengthen long-term data collection and awareness (Tampo *et al*. 2021). Policy initiatives like the EU Water Framework Directive and IPBES assessments underscore the importance of protecting freshwater insect biodiversity as a foundation for ecosystem integrity and water security.

Bio-Inspiration

Bio-inspiration (biomimicry/biomimetics) uses principles, structures and strategies evolved by organisms to solve human design challenges. Insects — by virtue of their diversity, compact biomechanics, sensory suites and life-history strategies — have become a rich source of ideas for robotics, materials science, sensing, and agricultural innovation. Recent advances translate insect form and function (cuticle materials, wing aerodynamics, navigation algorithms, social foraging rules) into technologies that can improve efficiency, resilience and sustainability in a warming world.

Concept of biomimicry and ecological innovation

Biomimicry frames innovation as learning from nature's time-tested designs and systems rather than simply copying appearances; it emphasizes function, systems thinking and sustainability. Ecological innovation extends this by asking how design can emulate not only anatomical features but also ecological processes (redundancy, modularity, resource recycling) to build resilient technologies and socio-ecological systems. The insect world offers compact, low-energy solutions (e.g., efficient wing flapping, distributed sensing, decentralized control) that map well onto current engineering challenges in micro-robotics and adaptive materials.

Examples of bio-inspired designs from insect physiology and behavior

Practical examples are already numerous. Flapping-wing and micro-aerial robots draw directly from insect wing kinematics and flexible cuticle mechanics to achieve stable flight at small scales (MIT RoboBee and follow-on designs). These efforts have produced tiny flyers that mimic insect maneuverability and could someday assist with targeted pollination or monitoring tasks. In materials, insect cuticle proteins such as resilin and hierarchical composites inspire lightweight, tough and flexible biomaterials and adhesives for wearables and soft robotics (Zheng *et al*. 2025). Navigation algorithms inspired by insect mushroom-body learning and optic-flow processing are powering autonomous route-following and cheap sensor suites for small robots (Sun *et al*. 2023). Energy-autonomous prototypes (e.g., "RoBeetle" and water-feeding row-bot concepts) exploit simple biochemical or environmental energy sources, mirroring how some insects extract energy from low-quality resources (Axios/Wired reporting; research prototypes). These examples show direct translation from insect form and behaviour into engineering solutions.

Role of insects in advancing robotics, materials science, and agriculture

In robotics, insect models enable design of robust controllers, compliant structures and distributed swarm behaviours that operate with limited computation and power—qualities critical for fieldable micro-robots. In materials science, the study of cuticle microstructure and adhesive strategies informs development of scalable, biodegradable polymers and surface coatings with tunable stiffness and toughness (Zheng *et al*. 2025). In agriculture, insect-inspired tools range from autonomous pollination platforms (drones/robotic pollinators) to sensor networks modeled on insect olfaction for pest detection and precision application of inputs, offering ways to reduce chemical use while maintaining productivity. Together, these lines of work illustrate how insect biology accelerates cross-disciplinary innovation with direct applicability to climate adaptation and sustainable food systems.

Potential of pollinator-inspired technologies in climate adaptation

Pollinator-inspired technologies have potential as climate-adaptation tools when used thoughtfully: robotic or drone pollination could provide targeted pollination in regions where wild pollinators temporarily fail because of extreme weather, or help pollinate isolated high-value crops when phenological mismatches occur. Sensor systems derived from insect olfaction models can enable early pest or disease detection under changing climate regimes, permitting rapid, localized responses that reduce crop loss and pesticide use (Sun *et al.* 2023). However, these technologies are best viewed as *complements*—not replacements—for healthy pollinator populations; maintaining and restoring habitat and floral resources remains the primary, lowest-cost climate-resilient strategy. When integrated with ecological management, bio-inspired tools can increase redundancy and adaptive capacity in agroecosystems.

Ethical and sustainability considerations in bio-inspired research

Biomimicry raises ethical and sustainability questions that must be addressed proactively. Critics note risks including techno-centrism (favoring technological fixes over ecological restoration), bioprospecting without equitable benefit-sharing, and unforeseen ecological or social harms from deploying novel devices (Broeckhoven and Winters, 2023). There are also research-ethics questions about the use of insects in experiments (welfare, scaling lab findings to wild systems), and governance concerns where military or surveillance applications of insect-inspired devices could conflict with conservation goals (Tsikas, 2025). Sustainable biomimicry therefore requires interdisciplinary oversight, transparent stakeholder engagement, lifecycle impact assessment (energy, materials, end-of-life), and policies for fair access and benefit-sharing—ensuring innovations support biodiversity rather than substitute for or further degrade it.

Major Threats to Ecosystem Services

Ecosystem services delivered by insects and pollinators are being degraded worldwide by multiple, interacting threats. Habitat conversion and urban expansion, widespread agrochemical use, biological invasions and pathogens, and climate-driven changes in timing and ranges together erode the capacity of insect communities to provide pollination, pest control, decomposition and aquatic functions (IPBES, 2019; Hallmann *et al.* 2017). The most important threat categories and the mechanisms have been discussed below by which they undermine ecosystem services.

Habitat loss, fragmentation, and urbanization

Habitat loss and fragmentation are primary drivers of insect declines because they remove nesting and foraging resources, reduce population sizes and disrupt movement and gene flow. Conversion of diverse semi-natural habitats to monoculture cropland or urban development eliminates floral resource continuity and nesting substrates (e.g., bare ground, hollow stems, dead wood), which disproportionately affects specialist and ground-nesting pollinators. Fragmentation increases edge effects and isolates populations, making them more vulnerable to demographic stochasticity, local extirpation and reduced recolonization. Urbanization can create novel opportunities (urban pollinator gardens, green roofs) but often results in lower overall habitat quality and creates barriers to dispersal for many taxa, reducing regional service provision and altering community composition.

Pesticide use and agrochemical pollution

Widespread use of insecticides, fungicides and herbicides—particularly systemic classes such as neonicotinoids—has strong direct and indirect effects on non-target insects. Chronic exposure to sublethal concentrations impairs navigation, foraging, reproduction and immune function in bees and other beneficial insects, while repeated broad-spectrum applications kill predators, parasitoids and decomposers that sustain regulating services. Agrochemical runoff and mixtures of pesticides and fertilizers also degrade aquatic habitats, harming macroinvertebrate communities that perform water-purification and nutrient-cycling functions (Sadafale *et al.* 2025). Meta-analyses and long-term datasets implicate pesticide intensity, often together with habitat loss, as a major predictor of pollinator and insect biomass declines (Hallmann *et al.* 2017; Sadafale *et al.* 2025).

Climate change and phenological mismatches

Climate change alters temperature and precipitation regimes, driving poleward and elevational range shifts, changing voltinism (number of generations), and advancing or delaying seasonal activity for both plants and insects. When plants and their pollinators respond differently to warming, phenological mismatches can occur (e.g., earlier flowering while pollinators emerge at the same historical time), reducing temporal overlap and pollination efficiency for specialized interactions. Climate extremes (late frosts, droughts, intense storms, heatwaves) further increase interannual variability in pollinator populations and can disproportionately affect life stages (e.g., overwintering queens), making service provision less reliable. In combination with land-use change, climate impacts thus increase uncertainty in the delivery of pollination, pest control and decomposition services.

Invasive species and disease spread among pollinators

Invasive species and emerging pathogens are important, interacting threats. Non-native plants and animals can alter floral communities and resource availability, while invasive predators or competitors displace native insects. In managed and wild bees, the parasitic mite *Varroa destructor* and associated viruses (notably deformed wing virus, DWV) have driven large declines in honey bee health and colony survival, and can facilitate pathogen spillover to wild bee species. Global transport of managed pollinators and trade in plant material increases the risk of moving pests and pathogens across regions, compounding local pressures and sometimes undermining biological-control services as well as pollination (IPBES, 2019; Warner *et al.* 2024). Disease, invasions and the interactions among them frequently act synergistically with pesticides and habitat loss to accelerate declines.

Monoculture farming and lack of floral diversity

Monoculture systems—large areas planted to a single crop—tend to produce extended periods with little or no floral resources for pollinators and other beneficial insects, creating a *temporal* and *spatial* "resource desert" at the landscape scale (Manasa *et al*. 2021). Even when a crop is mass-flowering, the nectar/pollen it provides is usually available only for a short window; outside that window insects face food scarcity unless semi-natural habitats, field margins or diversified crops supply alternative forage (Sarkar *et al*. 2000; Maitra *et al.* 2001; Maitra and Gitari, 2020). Nutrient-intensive monocultures often favour fast-growing grasses or dense canopies that suppress wildflower establishment, and heavy fertilizer use further reduces flower abundance—effects that have been linked to declines in pollinator abundance and species richness (Manasa *et al*. 2020; Santosh *et al*. 2020).

A lack of floral diversity also reduces the temporal continuity and nutritional breadth of resources: many bee species require diverse pollen sources for larval development and immune competence, and simplified diets are associated with poorer bee health and reduced resilience to stressors. Conversely, studies and reviews show that increasing crop and floral diversity at field and landscape scales (intercropping, flower strips, hedgerows, crop rotations) increases pollinator richness, stabilizes pollination services, and can maintain production without large land set-asides.

Socio-economic and policy challenges in insect conservation

Insect conservation faces a suite of socioeconomic and policy barriers that limit effective action. Key challenges include: limited funding and institutional capacity for long-term monitoring (especially in tropical and low-income regions), inadequate integration of insect values into agricultural and development policies, and erroneous incentive structures that reward yield maximization over biodiversity. Farmers often make rational short-term choices (e.g., pesticide use, monoculture expansion) driven by market signals, credit constraints and risk aversion; without incentives or technical support, uptake of pollinator-friendly practices remains low.

Policy fragmentation is common: water, agriculture, biodiversity and chemical-safety policies are frequently managed in silos, producing regulatory gaps (e.g., pesticide approvals that ignore pollinator landscape needs). Capacity gaps in monitoring and data limit the evidence base for national policy: many countries lack standardized insect-monitoring programs or the budgets to implement them, which hampers adaptive management and priority setting. Social equity issues also arise — smallholders and marginal communities often bear disproportionate risks from pollinator declines yet receive the least support to adopt conservation measures. Addressing these socioeconomic and policy challenges therefore requires cross-sectoral policy alignment, targeted finance (payments for ecosystem services, subsidies for floral resources), extension services, and inclusion of insect indicators in national biodiversity and agricultural accounts (IPBES, 2019).

Global initiatives for protecting insect-mediated ecosystem services

A range of global and regional initiatives now target pollinators and insect-mediated services:

IPBES Pollinators Assessment (2016 deliverable) and Global Assessments (2019): IPBES synthesized the state of pollinators, drivers of decline and policy options, emphasizing the need for landscape restoration, reduced pesticide risk, diversified farming and improved monitoring. The assessment framed pollinator protection as essential for food security and biodiversity, and recommended integrated policy responses across sectors.

FAO — Global Action on Pollination Services / International Pollinator Initiative 2.0 (2018–2030): FAO coordinates guidance, country assessments and action planning to conserve managed and wild pollinators, including technical resources for pollinator-friendly farming, national pollinator assessments, and promotion of agri-environment measures (FAO, Pollination portal; International Pollinators Initiative 2.0). FAO also supports capacity building, good-practice toolkits and multi-stakeholder platforms to translate science into policy and practice.

Other multilateral and national efforts: The UN's designation of World Bee Day and inclusion of pollinator considerations in some national biodiversity strategies has raised visibility (UN, World Bee Day). Regional agri-environment schemes (EU), national agri-environment payments, and conservation programmes increasingly include flower strips, hedgerows and pesticide stewardship as eligible measures. Additionally, scientific networks and citizen-science initiatives (e.g., national bee atlases, macroinvertebrate monitoring schemes) are expanding data flows that feed policy.

These initiatives share common priorities: (1) mainstreaming pollinator needs into agriculture and land-use planning; (2) reducing pesticide risks and promoting IPM; (3) restoring and managing floral and nesting habitats across landscapes; (4) strengthening monitoring and knowledge exchange; and (5) mobilizing finance and incentives for farmers and communities to adopt pollinator-friendly practices. While progress is tangible, implementation gaps remain—particularly in translating global recommendations into locally appropriate, funded actions in low-capacity regions—so continued investment in capacity building, policy integration and outcome-oriented monitoring is essential.

CONCLUSION

Insects play a foundational role in sustaining ecosystem services that are vital for biodiversity, agriculture, and human well-being. From pollination and decomposition to natural pest control and nutrient cycling, their contributions underpin ecological stability, productivity, and resilience. Pollinators, in particular, are indispensable for maintaining global food security and ensuring the reproduction of flowering plants. However, the growing pressures of habitat loss, monoculture farming, pesticide use, invasive species, and climate change have led to alarming declines in both the abundance and diversity of insect populations. These changes not only threaten ecological balance but also have direct economic and nutritional implications for human societies.

Decomposer insects support soil health and fertility, while aquatic insects play essential roles in nutrient cycling and water purification. Similarly, natural enemies such as predators and parasitoids regulate pest populations, reducing reliance on chemical pesticides and promoting sustainable agriculture. Insects have also inspired remarkable innovations in biomimicry, robotics, materials science, and ecological engineering, showing their potential beyond natural systems. Yet, the accelerating pace of environmental change is disrupting these delicate ecological relationships, leading to reduced efficiency of pollination, altered predator-prey dynamics, and the breakdown of key ecological processes.

Addressing these challenges requires urgent, coordinated action at local, national, and global levels. Conservation and management strategies should prioritize habitat restoration, diversification of agricultural landscapes, and reduction of harmful agrochemicals. Socioeconomic and policy frameworks must align to incentivize insect-friendly practices and strengthen monitoring systems. Global initiatives, such as those by IPBES and FAO, highlight the growing recognition of the need to safeguard insect-mediated services for sustainable food systems and ecosystem resilience. Ultimately, the protection of insects and their ecological functions is not only an environmental necessity but also a critical component of ensuring planetary health, food security, and climate resilience for future generations.

REFERENCES

Abrol, D.P. 2012. *Pollination biology: Biodiversity conservation and agricultural production*, Vol. 792. Springer Nature, New York, USA.

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A. and Klein, A.M. 2009. How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. *Ann. Bot.*, **103**(9): 1579–1588.

Assessment, M.E. 2001. *Millennium ecosystem assessment* (Vol. 2). Millennium Ecosystem Assessment.

Balfour, N.J., Harris, C., Storkey, J. and Ratnieks, F.L. 2025. Trade-off between pollinator-wildflower diversity and grassland yields. *NJP Biodiversity*, **4**(1): 1.

Bohan, D.A., Vacher, C., Tamaddoni-Nezhad, A., Raybould, A., Dumbrell, A.J. and Woodward, G. 2017. Next-generation global biomonitoring: Large-scale, automated reconstruction of ecological networks. *Trends Ecol. Evol.*, **32**(7): 477–487.

Bonacina, L., Fasano, F., Mezzanotte, V. and Fornaroli, R. 2023. Effects of water temperature on freshwater macroinvertebrates: A systematic review. *Biol. Rev.*, **98**(1): 191–221.

Brasil, L.S., Oliveira-Junior, J.M.B., Dias-Silva, K., Shimano, Y. and Juen, L. 2022. Insetos aquáticos bioindicadores de mudanças de uso da terra no Pará, Brasil: Evidências e perspectivas. *Oecologia Australis*, **26**(3): 424–444.

Brito, J.S., Cottenie, K., Brasil, L.S., Bastos, R.C., Ferreira, V.R.S., Cruz, G.M. and Juen, L. 2024. Main drivers of dragonflies and damselflies (Insecta; Odonata) metacommunities in streams inside protected areas in the Brazilian Amazon. *Environ. Monit. Assess.*, **196**(3): 281.

Broeckhoven, C. and Winters, S. 2023. Biomimethics: A critical perspective on the ethical implications of biomimetics in technological innovation. *Bioinspir. Biomim.*, **18**(5): 053001.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P. and Naeem, S. 2012. Biodiversity loss and its impact on humanity. *Nature*, **486**(7401): 59–67.

Chakravarty, T. and Gupta, S. 2024. Aquatic insects as indicators of water quality: Seasonal distribution and biomonitoring insights from a hilly river in the Eastern Himalayan region, India. *Clean Water*, **2**: 100056.

Chappa, L.R., Mugwe, J., Maitra, S. and Gitari, H.I. 2022. Current status and prospects of improving sunflower production in Tanzania through intercropping with sunnhemp. *Int. J. Biores. Sci.*, **9**(1): 1-8.

Das, S., Mitra, B., Saha, A., Mandal, S., Paul, P.K., El-Sharnouby, M., Hassan, M.M., Maitra, S., Hossain, A. 2021. Evaluation of quality parameters of seven processing type potato (*Solanum tuberosum* L.) cultivars in the Eastern Sub-Himalayan plains. *Foods*, **10**(5): 1138.

Devkota, K., Dos Santos, C.F., Ferreira, A.B. and Timberlake, T. P. 2024. Assessing the economic and nutritional value of pollination services in Nepal. *Sci. Rep.*, **14**(1): 25037.

Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Agard, J., Arneth, A. and Zayas, C.N. 2019. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science*, **366**(6471): eaax3100.

Dicks, L.V., Breeze, T.D., Ngo, H.T., Senapathi, D., An, J., Aizen, M.A. and Potts, S.G. 2021. A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nat. Ecol. Evol.*, **5**(10): 1453–1461.

Durgude, S.A., Ram, S., Kumar, R., Singh, S.V., Singh, V., Durgude, A.G., Pramanick, B., Maitra, S., Gaber, A. and Hossain, A. 2022. Synthesis of mesoporous silica and graphene-based FeO and ZnO nanocomposites for nutritional biofortification and sustained the productivity of rice (*Oryza sativa* L.), *Journal of Nanomaterials*, 2022, https://doi.org/10.1155/2022/5120307.

Gaikwad, D.J., Ubale, N.B. Pal, A., Singh, S., Ali, M.A. and Maitra, S. 2022. Abiotic stresses impact on major cereals and adaptation options - A review. *Res. Crop.*, **23**(4): 896-915.

Gallai, N., Salles, J.M., Settele, J. and Vaissière, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol. Econ.*, **68**(3): 810–821.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S.A. and Klein, A.M. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, **339**(6127): 1608–1611.

Gebremedhn, H., Hadgu, G. and Atsbha, T. 2025. Economic and nutritional value of insect pollination services in Ethiopia. *Sci. Rep.*, **15**(1): 35450.

Gitari, H.H., Nungula, E.Z., Chappa, L.R., Raza, M.A., Ranjan, S., Sow, S., Alnemari, A.M., Seleiman, M.F., Mwadalu, R. and Maitra, S., 2024. Agroforestry for climate security. *Agroforestry*, pp. 319-344.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N. and Schwan, H. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS One*, **12**(10): e0185809.

Hemasree, K.R., Sairam, M., Maitra, S., Ray, S., Maheswari, N., Gaikwad, D.J. and Santosh, D.T. 2025. Effects of sulphur and zinc on growth and productivity of summer cowpea under conditions of southern Odisha. *Crop Res.*, **60**: 28-34.

Hossain, A., Bhatt, R., Sarkar, S., Barman, M., Majumder, D., Saha, S., Islam, M., Maitra, S., Meena, R. S. 2021. Cost-Effective and Eco-Friendly Agricultural Technologies in Rice-Wheat Cropping Systems for Food and Environmental Security, In: Sustainable Intensification for Agroecosystem Services and Management, Jhariya, M.K., Banerjee, A., Meena, R. S.., Kumar, S., Ranj, A. (eds.), Springer, Singapore, pp. 69 - 96, https://doi.org/10.1007/978-981-16-3207-5_3.

Hwang, B.C., Giardina, C.P., Litton, C.M., Francisco, K.S., Pacheco, C., Thomas, N. and Metcalfe, D.B. 2022. Impacts of insect frass and cadavers on soil surface litter decomposition along a tropical forest temperature gradient. *Ecol. Evol.*, **12**(9): e9322.

IPBES. 2016. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. S.G. Potts, V. L. Imperatriz-Fonseca, and H. T. Ngo, (eds). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 552p.

IPBES. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.* IPBES Secretariat.

Johnson, M.F., Albertson, L.K., Algar, A.C., Dugdale, S.J., Edwards, P., England, J. and Wood, P.J. 2024. Rising water temperature in rivers: Ecological impacts and future resilience. *WIREs Water*, **11**(4): e1724.

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

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C. and Tscharntke, T. 2007. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B Biol. Sci.*, **274**(1608): 303–313.

Krishna, T.G., Maitra, S., Sairam, M., Gitari, H.I., Maheswari, N., Hemasree, K.R. and Ray, S. 2024. Precision nutrient management and plant stand influence the growth and productivity of maize under North Eastern Ghat Region of Odisha, India. *Int. J. Biores. Sci.*, **11**(02): 191-204.

Lautenbach, S., Seppelt, R., Liebscher, J. and Dormann, C.F. 2012. Spatial and temporal trends of global pollination benefit. *PLoS ONE*, **7**(4): e35954.

Lee, Y.D., Yokoi, T. and Nakazawa, T. 2024. A pollinator crisis can decrease plant abundance despite pollinators being herbivores at the larval stage. *Sci. Rep.*, **14**(1): 18523.

Losey, J.E. and Vaughan, M. 2006. The economic value of ecological services provided by insects. *BioSci.*, **56**(4): 311–323.

Maheswari, N., Maitra, S., Sairam, M., Ray, S., Sagar, L., Sanosh, D.T. and Gaikwad, D.J. 2025. Impact of real-time nitrogen management on the performance of maize-cowpea intercropping system. *Crop Res.*, **60**(3-4): 139-146.

Maitra, S., Sahoo, U., Sairam, M., Gitari, H.I., Rezaei-Chiyaneh, E., Battaglia, M.L. and Hossain, A. 2023a. Cultivating sustainability: A comprehensive review on intercropping in a changing climate. *Res. Crop*. **24**(4): 702-715.

Maitra, S. and Ghosh, D.C. and Sounda, G. and Jana, P.K. 2001. Performance of intercropping legumes in finger millet (*Eleusine coracana*) at varying fertility levels. *Indian J. Agron.*, **46**(1): 38-44.

Maitra, S. and Gitari, H.I. 2020. Scope for adoption of intercropping system in organic agriculture. *Indian J. Nat. Sci.*, **11**(63): 28624 - 28631.

Maitra, S. and Ray, D.P. 2019. Enrichment of biodiversity, influence in microbial population dynamics of soil and nutrient utilization in cereal-legume intercropping systems: A Review, *Int. J. Biores. Sci.*, **6**(1): 11-19.

Maitra, S. and Zaman, A. 2017. Brown manuring, an effective technique for yield sustainability and weed management of cereal crops: A review. *Int. J. Biores. Sci.*, **4**(1): 1-5.

Maitra, S., Praharaj, S., Brestic, M., Sahoo, R.K., Sagar, L., Shankar, T., Jnana Bharati Palai, J.B., Sahoo, U., Sairam, M., Pramanick, B., Nath, S., Venugopalan, V.K., Skalický, M. and Hossain, A. 2023b. Rhizobium as biotechnological tools for green solutions: An environmentfriendly approach for sustainable crop production in the modern era of climate change. *Curr. Microbiol.*, **80**: 219.

Maitra, S., Ray, S., Sagar, L., Sairam, M., Pramanick, B., Gitari, H.I., Santosh, D.T., Gaikwad, D.J., Atapattu, A., Chappa, L.R. 2025a Cropping system approach in climate-resilient food crop production. *In:* Sustainability sciences in Asia and Africa. Springer, pp. 327–356. https://doi.org/10.1007/978-981-96-7699-6_15

Maitra, S., Sairam, M., Ray, S., Santosh, D.T., Gaikwad, D.J., Gitari, H., Mukesh, G. and Maheswari, N. 2024. Applauding soil quality improvement through legume-based intercropping system: A review. *Int. J. Biores. Sci.*, **11**: 59-69.

Maitra, S., Sairam, M., Sagar, L., Ray, S., Santosh, D.T., Gaikwad, D.J., Atapattu, A.J. and Gitari, H.I. 2025b. Alley Cropping: A Sustainable Agroforestry System for Enhancing Productivity, Soil Health and Biodiversity. In *Plant Biotechnology and Sustainable Agriculture: Bridging the Gap for Global Food Security*, CABI, pp. 235-248).

Maitra, S., Samui, S.K., Roy, D.K. and Mondal, A.K. 2001. Effect of cotton-based intercropping system under rainfed conditions in *Sundarban* region of West Bengal. *Indian Agric.*, **45**(3–4): 157–162.

Maitra, S., Zaman, A., Mandal, T.K. and Palai, J.B. 2018. Green manures in agriculture: A review. *J. Pharmacog. Phytochem.*, **7**(5): 1319-1327.

Manasa, P., Maitra, S. and Barman S. 2020. Yield attributes, yield, competitive ability and economics of summer maize-legume intercropping system. *International Journal of Agriculture Environment and Biotechnology*, **13**(1): 33 - 38.

Manasa, P., Maitra, S. and Reddy M.D. 2018. Effect of summer maize-legume intercropping system on growth, productivity and competitive ability of crops. *Int. J. Manage. Technol. Engg.*, **8**(12): 2871-2875.

Manasa, P., Sairam, M. and Maitra, S. 2021. Influence of Maize-Legume Intercropping System on Growth and Productivity of Crops. *Int. J. Biores. Sci.*, **8**(1): 47 - 60.

Mansier, L. and van Rijn, P.C. 2024. Modelling agricultural landscape complementation for natural pest control. *J. Appl. Ecol.*, **61**(11): 2701–2716.

Mohanty, S.S., Dash, N., Nanda, S.P. and Dey, R.K. 2016. Synthesis, characterization and removal of heavy metal ions from water bodies using novel hybrid materials bases on silica. *ISOR Journal of Applied Chemistry*, **9**(10): pp.2278-5736.

Mukesh, G., Sairam, M., Maitra, S., Gaikwad, D.J., Sagar, L. and Ray, S., 2024. Agrometeorological indices, physiological growth parameters, and performance of finger millet as influenced by different cultivars under hot and subhumid region of Odisha. *Int. J. Exp. Res. Rev.*, **42**: 148-161.

Nanda, S.P., Padhy, A.K. and Dey, R.K. 2010. Synthesis of some benzothiazolyl and imidazole derivatives and evaluation of antibacterial activities. *J. Chem. Pharm. Res.*, **2**: 785-792.

Ngugi, M.M., Muui, C., Gweyi-Onyango, J.P., Maitra, S. and Gitari, H.I. 2022. Influence of silicon on translocation, compartmentation and uptake of lead in leafy vegetables. *Int. J. Agric., Environ. Biotechnol.*, **15**(01): 33-50.

Nichols, E.S. and Gardner, T.A. 2011. Dung beetles as a candidate study taxon in applied biodiversity conservation research. In *Ecology and evolution of dung beetles* (pp. 267–291). Wiley-Blackwell.

Nichols, E., Spector, S., Louzada, J., Larsen, T., Amezquita, S., Favila, M.E. and Network, T. S. R. 2008. Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. *Biol. Conserv.*, **141**(6): 1461–1474.

Nungula, E.Z., Mugwe, J., Nasar, J., Massawe, B.H., Karuma, A.N., Maitra, S., Seleiman, M.F., Dindaroglu, T., Khan, N. and Gitari, H.I. 2023. Land degradation unmasked as the key constraint in sunflower (*Helianthus annus*) production: Role of GIS in Revitalizing this vital sector. *Cogent Food Agric.*, **9**(2):2267863.

Ollerton, J., Winfree, R. and Tarrant, S. 2011. How many flowering plants are pollinated by animals? *Oikos*, **120**(3): 321–326.

Palmer, C.A., Orwig, D.A., McIntire, C.D. and Keiser, A.D. 2025. Decomposer functional breadth maintains litter decomposition patterns three decades after Eastern Hemlock decline. *Soil Biol. Biochem*, 109943.

Perveen, I., Ismail, K., Abbas, N., Saleem, Y., Riaz, S., Ayaz, A. and Abidi, S.H.I. 2025. Biochemistry in soil science: Enzyme activities, nutrient cycling. In *Soils and Sustainable Agriculture: Interplay of Soil, Plant, Water and Environmental Systems For Sustainable Agriculture*, Springer Nature Switzerland, pp. 1095–1112.

Pires, C.S.S. and Maués, M.M. 2020. Insect pollinators, major threats and mitigation measures. *Neotrop. Entomol.*, **49**(4): 469–471.

Ray, S., Maitra, S., Sairam, M., Sameer, S., Sagar, L., Divya, B.S. and Gitari, H.I. 2025. The nexus between intercropping systems, ecosystem services and sustainable agriculture: A review. *Research on Crops,* **26**(1): 1-11.

Ray, S., Maitra, S., Sairam, M., Sravya, M., Priyadarshini, A., Shubhadarshi, S. and Padhi, D.P. 2024. An unravelled potential of foliar application of micro and beneficial nutrients in cereals for ensuring food and nutritional security. *Int. J. Exp. Res. Rev.*, **41**(Spl.): 19–42.

Reid, W.V. 2006. The Millennium Ecosystem Assessment: Overview of findings. *The Millennium Ecosystem Assessment: Implications for Belgium*, **25**.

Roh, D., Kim, S., Kim, H.S., Han, S.H., Kim, G. and Son, Y. 2024. The effects of termites and beetle larvae on the decomposition of *Pinus densiflora* and *Quercus acutissima* in South Korea over a 6-year period. *Diversity*, **16**(8): 452.

Roubik, D.W. 1992. *Ecology and natural history of tropical bees.* Cambridge University Press.

Sadafale, G.V.R., Vishnupandi, M., Ab+, S., Sudalaiyandi, Y., Subal, B.K., Kamal, P.A. and Shukla, A. 2025. Global decline of pollinators: Drivers, consequences and mitigation strategies. *J. Biol. Nat.*, **17**(2): 356–379.

Sahu, S., Nanda, S.P. and Padhy, R.K. 2024. Interfacial Micro-heterogeneous Surface Phenomenon in the Oxidative Transformation of 2-Phenylethanol by Ce (IV). *Chem. Africa*, **7**(3): 1605-1617.

Sairam, M., Maitra, S., Sagar, L., Biswas, T., Bárek, V., Brestic, M. and Hossain, A. 2025. Application of precision nutrient tools for the optimization of fertilizer requirements and assessment of the growth and productivity of maize (*Zea mays* L.) in the northeastern Ghat of India. *J. Agric. Food Res.*, 101958.

Santosh, D.T., Debnath, S., Maitra, S., Sairam, M., Sagar, L. L., Hossain, A. and Moulick, D. 2024. Alleviation of climate catastrophe in agriculture through adoption of climate-smart technologies. *In:* Climate Crisis: Adaptive Approaches and Sustainability. (Eds; Chatterjee, U., Shaw, R., Kumar, S., Raj, A. D. and Das, S.) Springer Nature Switzerland. pp. 307-32. https://doi.org/10.1007/978-3-031-44397-8_17.

Santosh, D.T., Maitra, S. and Tiwari, K.N. 2023. Optimizing nutrients through drip fertigation and plastic mulch on the growth and yield in banana (*Musa acuminata* L.). *Res. Crop.*, **24**: 330-336.

Santosh, D.T., Sain, S. and Maitra, S. 2022. Estimation of crop water requirement in maize and chickpea for different patterns of intercropping. *Ind. J. Nat. Sci.*, **13**(71): 41392-41398.

Sarkar, B.C., Manohar, K.A., Shukla, G., Maitra, S., Dabral, A., Sairam, M. and Chakravarty, S. 2024. Benefactions of Agroforestry to Ecosystem Services. In *Agroforestry to Combat Global Challenges: Current Prospects and Future Challenges*, Springer Nature, Singapore, pp. 129-146.

Sarkar, R.K., Shit, D. and Maitra, S. 2000. Competition functions, productivity and economics of chickpea (*Cicer arietinum*)-based intercropping system under rainfed conditions of Bihar plateau. *Indian J. Agron.*, **45**(4): 681-686.

Sentis, A., Hemptinne, J.L., Magro, A. and Outreman, Y. 2022. Biological control needs evolutionary perspectives of ecological interactions. *Evol. Appl.*, **15**(10): 1537–1554.

Settele, J., Bishop, J. and Potts, S.G. 2016. Climate change impacts on pollination. *Nat. Plants*, **2**(7): 1–3.

Sun, X., Fu, Q., Peng, J. and Yue, S. 2023. An insect-inspired model facilitating autonomous navigation by incorporating goal approaching and collision avoidance. *Neural Netw.*, **165**: 106–118.

Tampo, L., Kaboré, I., Alhassan, E.H., Ouéda, A., Bawa, L.M. and Djaneye-Boundjou, G. 2021. Benthic macroinvertebrates as ecological indicators: Their sensitivity to the water quality and human disturbances in a tropical river. *Front. Water*, **3**: 662765.

Tsikas, A. 2025. Insects in scientific research: A philosophical examination through the lens of the 3Rs. *Bioethica.*, **11**(1): 21–34.

Vanbergen, A.J., Espíndola, A. and Aizen, M.A. 2018. Risks to pollinators and pollination from invasive alien species. *Nat. Ecol. Evol.*, **2**(1): 16–25.

Wagner, D.L., Grames, E.M., Forister, M.L., Berenbaum, M.R. and Stopak, D. 2021. Insect decline in the Anthropocene: Death by a thousand cuts. *Proc. Natl. Acad. Sci.*, **118**(2): e2023989118.

Wyckhuys, K.A., Bushley, K., Gratton, C., Gurr, G.M., Pozsgai, G., Tscharntke, T. and Elkahky, M. 2025. Restoring functional farmland biodiversity for biological pest control. *Trends Plant Sci.*, **30**(10): 1097-1110.

Zaman, A., Zaman, P. and Maitra, S. 2017. Water resource development and management for agricultural sustainability. *J. Appl. Adv. Res.*, **2**(2): 73-77.

Zheng, Y., Wang, J., Wang, J., Li, Y. and Jiang, Z. 2025. Insect cuticle: A source of inspiration for biomimetic interface material design. *Colloid Interface Sci. Commun.*, **64**: 100818.