Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 3, Issue 9, 2025

POLLINATORS, PREDATORS, AND PROTECTORS: BENEFICIAL INSECTS AS DRIVERS OF SUSTAINABLE FRUIT PRODUCTION

Shay Chirag[*1], Parvez Jan[2], Noman Basheer[3], Israr Ullah[4], Aziz Ullah[5], Eid Muhammad[6], Sajid Ali Shah[7], Fayyaz Maqbool[8], Jabir Asghar[9], Hanan Khalid[*10]

[*1]*Department of Entomology Agriculture University of Faisalabad*
[2]*Institute of horticultural sciences University of agriculture Faisalabad*
[3]*Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad-Pakistan*
[4]*Agriculture and Cooperative Department Balochistan*
[5]*Department of Horticulture, Lasbela University of Agriculture, Water & Marine Science, Uthal*
[6] *Institute of Horticultural science University of Agriculture Faisalabad Pakistan*
[7]*Department of Agriculture. University college of Dera Murad Jamali Naseer Abad Baluchistan*
[8]*Department: Entomology, Faculty: Crop protection Sindh Agriculture University Tandojam*
[9]*Southwest University of Science and technology China*
[10]*University of Agriculture Faisalabad*

[*1]shay33chirag44@gmail.com; [2]parvezjan032@gmail.com; [3]noumanbaloch266@gmail.com; [4]israrullah530@gmail.com; [5]azizullahshaheen00@gmail.com; [6]eidmuhd20@gmail.com; [7]syedsajid@ucdmj.luawms.edu.pk; [8]fayyazmaqboolf2@gmail.com; [9]jmengal456@gmail.com; [10]hananentomologist@gmail.com

DOI: https://doi.org/10.5281/zenodo.17164408

Keywords
Pollinators, Predators, Parasitoids, Beneficial Insects, Fruit Production

Article History
Received: 05 July 2025
Accepted: 05 September 2025
Published: 20 September 2025

Copyright @Author

Corresponding Author: *
Shay Chirag

Abstract

Beneficial insects are a pillar of sustainability and productivity of fruit crops due to services they provide such as pollination, natural biological control and ecological balance maintenance on produce. The review below looks at the diversity and functional groups of these insects; namely pollinators, predators, parasitoids, and soil enhancer beneficial insects in different cropping systems of fruits. It shows that the availability of such organisms results in an increase in the yield of the fruits, their quality, and lower usage of chemicals. However, such important partners are facing a plethora of hazards, such as habitat loss, pesticide sprays, global warming, and monoculture farming. Limiting the negative impacts of these issues have led to severe loss of beneficial insects in crops thus disturbing production and the well-being of an ecosystem, and to curb increasing problems, the review echoes the need of conservation efforts that are specific and are aimed at supporting and protecting beneficial insects in fruit orchards. The use of floral strips, cover crops, intercropping, and minimal tillage that are part of the practices involved in habitat management are highlighted to be useful in increasing insect biodiversity and ecosystem services. Along with this, holistic ways of ensuring that ecological knowledge is combined with practical practices in farming are being regarded as crucial in maintaining insect populations in long-term basis. Two rationales can be used to infer that

growers and researchers can plan landscapes and practices by following the above approaches, knowing the characteristics of beneficial insects' types found in fruit systems and the roles they play. The purpose of this review is to gap the understanding into the field practice, which would lead into more resilient and productive fruit farming.

INTRODUCTION

Being among the key pillars of global agriculture, fruit crops provide essential nutrients, economic value, and livelihoods to millions of farming families worldwide (Sharma, Meena, & Bhati, 2017). Fruit cultivation occurs across diverse agroecological systems, ranging from extensive traditional orchards and large-scale horticultural operations to small, intensive farms. In 2020, approximately 90.6 million hectares of fruit were cultivated globally, producing around 887 million metric tons annually (FAO, 2022). In this context, the horticulture industry is a significant component of Pakistan's agricultural economy it contributes about 12 % of agricultural GDP and operates within a sector that provides employment to roughly 38 % of the country's workforce (Ahmad et al., 2023; Ministry of Commerce, 2023). Pakistan's diverse agro-climatic zones ranging from subtropical lowlands to temperate highlands create ideal conditions for cultivating a wide range of fruit crops (Shah et al., 2022; Cheema & Jamali, 2020). The country ranks among the top global producers of several commercial fruits, including mango, citrus, dates, and guava, while apples, pomegranates, and bananas also contribute significantly to the fruit sector (Shah et al., 2022; Zahoor et al., 2023; Yousaf et al., 2023).

A major biological limitation to sustainable fruit production worldwide is pest pressure from key species such as fruit flies (*Tephritidae*) in mango and guava, and mealybugs (*Pseudococcidae*) in citrus that can cause significant yield loss. In Pakistan, *Bactrocera dorsalis* and *B. zonata* infestations have been reported to result in 5–100% fruit loss, with infestation levels as high as 51–67% in guava and 31–46% in mango orchards. In various mango systems, farms have experienced fruit damage levels of up to 50%, with a notable 40.6% of cases exceeding that threshold (Khan et al., 2001; Reig et al., 2015; Kakade et al., 2021).The problem is enhanced in Pakistan as climate change has led to changes in pest phenology, geographical range expansion of local pests, and invasion of exotic species, which are becoming prevalent in the fruit growing areas of the country (Masood et al., 2022; Jan et al ., 2025).Traditional management of fruit crops in Pakistan frequently relies on calendar/schedule-based, intensive insecticide applications, which has led to documented pesticide overuse and high spray frequencies in citrus orchards (Tariq et al., 2007; Meena et al., 2025). At the regional level, Asia accounts for the largest volumes and highest average pesticide use per unit cropland area globally, underscoring the intensity of pesticide dependence in the region (Food and Agriculture Organization ,2023).

The reliance on broad-spectrum insecticides can trigger a vicious cycle: by killing natural enemies these sprays often precipitate secondary pest outbreaks (e.g., whiteflies and scale insects in mango), which in turn prompt successive rounds of chemical applications (Gross & Rosenheim, 2011; Sánchez-Bayo, 2021; Sani et al., 2020). Regional and national studies from South Asia also document rising whitefly/scale problems and insecticide resistance that are consistent with such pesticide-driven resurgence dynamics (Mahmood et al., 2022; Otieno, 2021). Pesticide residues have been aslo found in agricultural soils of Swat Valley, Pakistan, posing risks to both the environment and human health (Nafees et al., 2008). Groundwater contamination has also been documented in various agricultural regions, with residues detected in multiple pesticide groups, raising concerns about potable water quality (Javaid et al., 2023). Moreover, chronic exposure among farm workers in Swat has been linked to reduced haemoglobin levels and impaired liver and kidney functions (Khan et al., 2013). These pressures are compounded by structural ecological degradation, such as the monocultural nature of the landscape and the fragmentation of habitats, which reduce

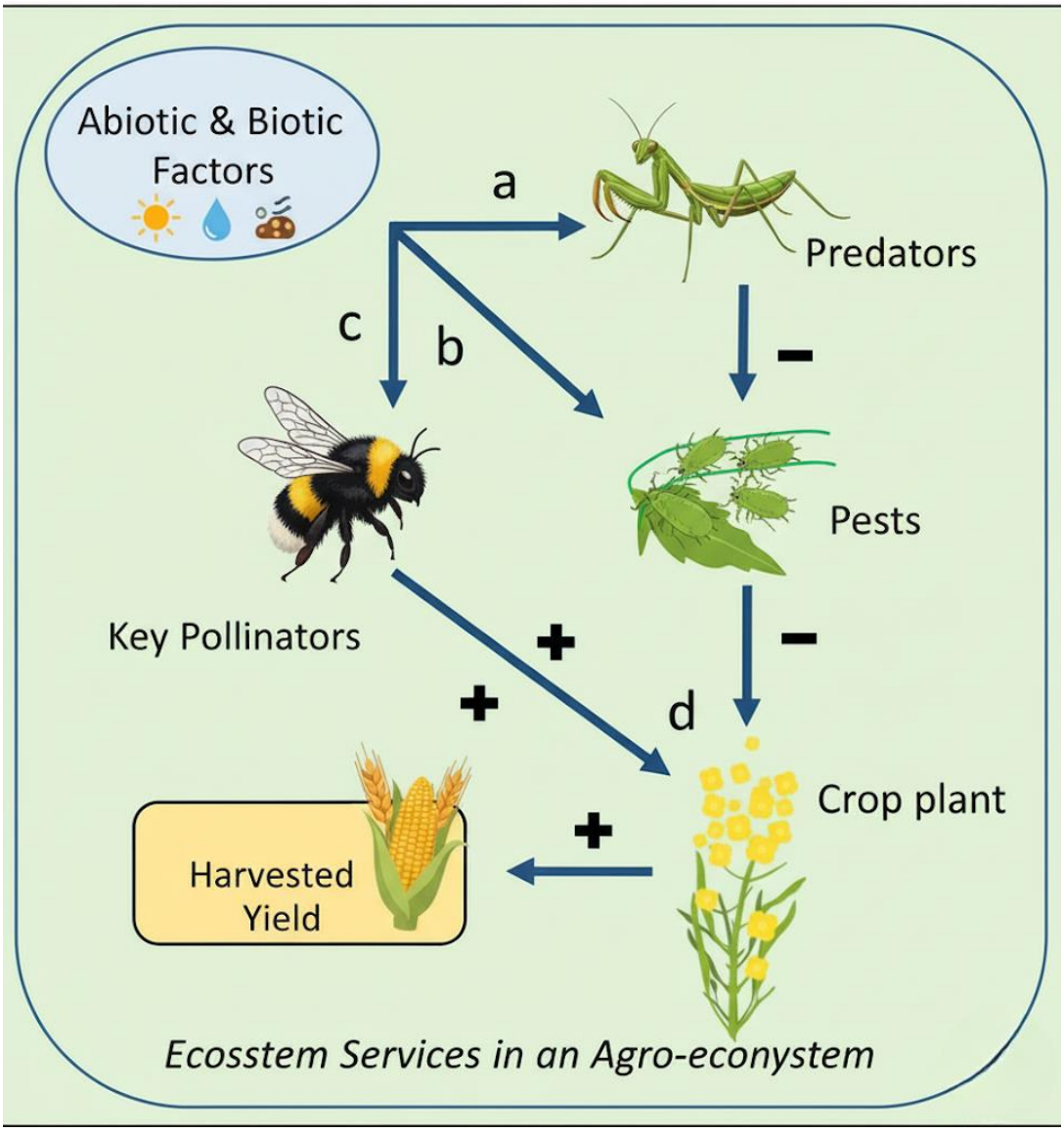
biodiversity and connectivity between ecosystems (Tscharntke et al., 2005; Haddad et al., 2015). Intensive tillage and the resulting decline in soil organic carbon (reported losses can reach 20–60%) combined with reduced organic matter inputs, undermine soil health, fertility, and the resilience of production systems (Yellajosula et al., 2020; Beillouin et al., 2023; Hussain et al., 2021). The challenges are especially sharp in Pakistan because many farmers have low awareness of ecological and agroecological options, which reduces adoption of nonchemical practices (Ullah et al., 2022; Jan et al., 2025). Weak and uneven extension/technical-assistance systems and policy environments that have historically favoured chemical solutions over integrated or agroecological approaches further limit uptake, despite growing evidence that chemical-dominant strategies produce counterproductive social, environmental and health outcomes (Davidson et al., 2001; Dabholkar et al., 2023; Noman et al., 2024).

Integration of beneficial insects into fruit production enhances agroecological sustainability by improving productivity, economic returns, and environmental integrity (Queirós et al., 2024). Pollination services have a direct impact on yield stability and fruit quality; diverse pollinator communities can boost fruit set, sugar content, size uniformity, and induce early ripening traits that premium markets demand for export competitiveness (Queirós et al., 2024; Anees et al., 2022). In Pakistan, crops dependent on pollinators deliver significantly better outcomes. In strawberries, open pollination led to 26% higher total soluble solids and longer shelf life compared to pollinator-excluded fruits (Anees et al., 2022). Predators and parasitoids play a key role in reducing the reliance on synthetic insecticides, thereby lowering input costs and limiting environmental contamination. In Pakistan, well-implemented IPM strategies combining biological control, cultural practices, and selective chemical use have reduced pesticide applications by up to 87% while increasing crop yields by 10–25% (Noman et al., 2024). Specifically, in citrus IPM programs across Punjab, integrating sanitation, pheromone traps, protein baits, and botanical extracts has reduced reliance on chemical pesticides while maintaining high yields (Abbas et al., 2021). Agroecological strategies such as diversified cropping systems, animal integration, organic soil management, and enhanced biodiversity not only improve agronomic performance but also fortify system resilience against climate stressors (Altieri et al., 2015). Embedded biodiversity including arthropods and soil biota plays a vital role in stabilizing agricultural production systems and maintaining soil functions essential for adapting to climate variability (Liu & Yang, 2023).

Although empirical studies demonstrate the economic and ecological value of beneficial insects in fruit production such as the effective use of indigenous parasitoids against pomegranate pests (Mahmood et al., 2021). Their widespread adoption remains limited in Pakistan due to fragmented pest management and weak integration of ecological strategies (Aziz & Hussain, 2018). The limited stakeholder awareness further constrains uptake of sustainable pest-management approaches; for instance, a recent survey in Punjab reported that 65.3% of farmers had no knowledge of biological control and most had never received training from extension services (Bakhtawer & Afsheen, 2021) .While another study found that only 11% of cucurbit growers could correctly identify bees used here as proxies for beneficial insect guilds highlighting critical knowledge gaps tied to weak extension and inadequate grower training (Ali et al., 2020). There is a clear lack of policy support: Pakistan's current subsidies disproportionately favor chemical inputs such as fertilizers and pesticides while initiatives for long-term, habitat-based, or ecological solutions receive little attention (World Bank Group, 2022; Associated Press of Pakistan, 2025). Moreover, public awareness of sustainably grown fruits and the ecological services supporting fruit production remains low, resulting in undervaluation of such products in markets (World Bank Group, 2022). Despite Pakistan's rich biodiversity with over 954 species of beneficial insects across ten orders offering strong potential for biological control and pollination research and policy continue to prioritize pesticide use over ecological approaches (Suhail et al., 2010; Jan et al., 2025).

The current review collates the available information regarding the role of beneficial insects in sustainable fruit production and specifically how it upholds relevance in horticultural industry in Pakistan. It explains manner in which pollinators, predators, and parasitoids as well as decomposers improve fruit productivity in aiding realization of ecological balance. Conservation measures such as habitat manipulation, and the use of low-risk pesticides. the review admits the concept of a system of integrated pests and pollinator management that provides benefits to the ecosystem services, reduces the use of chemicals, and increases the resilience of the fruit harvest considering the changes in climatic conditions. The results of this study can serve as the basis of the establishment of sustainable and climate-resilient horticultural practices, specifically, in biodiversity hotspots and vulnerable agroecosystems.

Figure.1.1 Pollinators, Predators, and Protectors: Enhancing Sustainable Agro-Ecosystems through Beneficial Insects.



Types of Beneficial Insects in Fruit Crops and Their Roles

Useful insects are essential partners in fruit orchard ecosystems, playing a part in natural pest control, pollination, and improving orchard soils while maintaining overall biodiversity. They are a cornerstone of ecological stability in orchards, reducing the need for synthetic inputs and increasing resilience to pest outbreaks caused by environmental stressors (Gurr et al., 2017). These insects are generally classified into four functional groups: pollinators, which facilitate plant reproduction; predators, which actively consume pests; parasitoids, which regulate pest abundance via host parasitism; and soil enhancers, which improve fertility and soil structure. All these groups act synergistically to maintain productivity and support integrated pest management (IPM) (Tschumi et al., 2016). Creating diverse habitats, maintaining floral sources throughout the year, and reducing pesticide use allow fruit growers to sustain healthy populations of beneficial insects, leading to long-term economic and ecological benefits (Tamburini et al., 2020).

Pollinators: The sexual reproduction of a number of fruit crops requires the activity of pollinators that move pollen between flowers and hence fruiting, seed production, and fruit quality (Garibaldi et al., 2013). Apple (*Malus domestica*), pears (*Pyrus communis*), cherries (*Prunus avium*), plums (*Prunus domestica*), and almonds (*Prunus dulcis*) are orchard species that heavily rely on insect pollination. The most commonly used pollinators are managed honey bees (*Apis mellifera*) because of their ease of transport and suitability for various crops. Nevertheless, in landscapes with a wide variety of floral resources and little exposure to pesticides, honey-bee pollinators are commonly outperformed by wild pollinator species like bumblebees (*Bombus* spp.) and solitary bees such as the blue orchard bee (*Osmia lignaria*) in pollination efficiency (Dainese et al., 2019). *O. lignaria* is especially useful with early crops, because it forages during cooler weather, demonstrates floral fidelity, and can be maintained using artificial nesting cavities (MacIvor & Packer, 2015). Pollinators increase yield besides promoting fruit size, seed number, and uniformity. Conservation measures, including hedgerow and wildflower strip planting, minimizing the use of chemicals during bloom, and other habitat enhancement methods, are critical to maintaining pollinator diversity and richness (Nicholls & Altieri, 2004). The natural pollination services facilitated by pollinators in IPM systems minimize reliance on non-natural resources and act as a buffer against climate variability effects (Tamburini et al., 2020).

Predators: Orchard predacious insects form a natural defense mechanism of the orchard against pests by feeding on a diverse variety of species and keeping pest populations below economic thresholds (Snyder, 2019). Coccinellidae (ladybird beetles), including *Coccinella septempunctata* and *Harmonia axyridis*, are effective predators of aphids, scale insects and whiteflies, especially early in the growing season (Obrycki & Kring, 1998). Green lacewings (Chrysopidae) are valued because their larvae ("aphid lions") feed on large quantities of aphids, thrips and mealybugs, while adults feed on nectar and pollen. Hoverflies (*Syrphidae*) benefit orchards both as pollinators in the adult stage and as aphid predators in the larval stage (Reemer & Rotheray, 2009). Ground beetles (*Carabidae*) and rove beetles (*Staphylinidae*) forage on the orchard floor, preying on soil-dwelling pest stages such as cutworms and codling moth pupae and disrupting pest life cycles (Hole et al., 2005). Habitat management practices that enhance predator abundance and diversity include planting flowering strips, intercropping, mulching, and reducing tillage (Tschumi et al., 2016). These measures provide cover, nectar, and alternative food resources that support healthy predator populations and help suppress pests without chemical interventions.

Parasitoids: Parasitoids are insects and lay their eggs either on or inside of the host pests, and as they develop, the larvae kill the host. This type of biological control is very specific and has the potential of greatly decreasing pests (Gurr et al., 2017). Parasitoid wasps belonging to Braconidae and Ichneumonidae in fruit orchards prey on larvae of lepidopteran pests. These include the codling moth (Cydia pomonella) and leafrollers. The Encyrtidae and Aphelinidae are members of the groups; scales and mealybugs are important pests in

citrus and pome fruit orchards. Parasitoid wasps known as egg parasitoids, like Trichogramma spp., represent a common element of biological control initiatives including the deterrence of lepidopteran pests prior to their emergence and are therefore particular accordingly valuable in natural systems (Jonsson et al., 2021). An outstanding case is that of Diachasmimorpha longicaudata a braconid wasp which has been widely used in augmentative releases to make tephritid fruit flies in citrus and mango orchards (Landis et al., 2000). Habitat complexity is critical in determining the success of parasitoids in orchards since this habitat contributes to floral resources that adult parasitoids use due to feeding and refuge habitats where they reproduce. The minimization of the pesticide use and preserving the flowering vegetation with nectar increases the parasitoid effectiveness and durability (Nicholls & Altieri, 2004).

Soil Enhancing Beneficial Insects: Soil-active beneficial insects play several complementary roles that keep orchards healthy: they accelerate nutrient cycling and organic-matter decomposition, suppress soil-dwelling pest stages (for example pupae and larvae of codling moths and cutworms), and create soil-microhabitat heterogeneity that improves root penetration and water holding capacity. Epigeal predators such as ground beetles (Carabidae) and rove beetles (Staphylinidae) commonly consume overwintering larvae and pupae of orchard pests, reducing pest emergence (Riddick & Mills, 1994; Stocker, Barthold & Betz, 2022). Dung beetles (Scarabaeidae and allies) bury and mix dung into the soil, increasing nutrient availability and microbial activity and as recent meta-analysis shows often enhancing plant growth under field/experimental conditions (Anderson et al., 2024). Detritivores (many beetle taxa) and ants accelerate litter breakdown and stimulate microbial decomposition and humus formation, creating nutrient hotspots that benefit tree roots and overall soil fertility (Luo et al., 2023; Meurer et al., 2020). The digging and bioturbation behaviour of soil arthropods reduces compaction and improves pore structure and root access; management practices that conserve these organisms' conservation/no-till, organic mulches, permanent ground cover, and reduced use of broad-spectrum insecticides reliably increase their abundance or activity in many systems (Meurer et al., 2020; Bengtsson, Ahnström & Weibull, 2005).

IEER
Institute for Excellence in Education & Research

Table: 01. Beneficial Insects in Fruit Crops

Sr. No.	Common Name	Scientific Name	Use/function	Associated Fruit Crops
1	Honeybee	*Apis mellifera*	~ (Pollinator)	Apple, Guava, Citrus, Pomegranate
2	Solitary Bee	*Osmia cornuta*	Pollinator	Apple, Apricot
3	Drone Fly	*Eristalis tenax*	Pollinator	Mango, Date Palm
4	Ladybird Beetle	*Coccinella septempunctata*	Aphids, Whiteflies, Scales	Guava, Citrus, Pomegranate
5	Variegated Lady Beetle	*Hippodamia variegata*	Aphids, Psyllids	Guava, Citrus
6	Green Lacewing	*Chrysoperla carnea*	Mealybugs, Thrips, Whiteflies	Mango, Apple, Guava
7	Minute Pirate Bug	*Orius insidiosus*	Thrips, Mites, Aphids	Citrus, Grapes
8	Egg Parasitoid	*Trichogramma chilonis*	Fruit borers (Helicoverpa, Ectomyelois)	Pomegranate, Date Palm
9	Egg Parasitoid	*Trichogramma evanescens*	Lesser Date Moth	Date Palm

			(Batrachedra amydraula)	
10	Aphid Parasitoid	*Aphidius colemani*	Aphids (Aphis gossypii, etc.)	Citrus, Apple
11	Mealybug Parasitoid	*Anagyrus kamali*	Pink hibiscus mealybug (Maconellicoccus hirsutus)	Guava, Citrus, Pomegranate
12	Dung Beetle	*Onthophagus gazella*	– (Soil enhancer, pest reduction)	General Orchard Soil Health
13	Termite (Beneficial species)	*Macrotermes spp.*	Organic debris decomposer	Mango, Date Palm orchards
14	Ant (Soil-aiding species)	*Solenopsis spp.*	Soil pest larvae (indirect role)	Mango, Apple

Source: (Meyerdirk, 2001).

Impact of Beneficial Insects on Fruit Yield and Quality

Beneficial insects strongly influence both fruit yield and fruit quality because they provide pollination and pest suppression services that directly affect fruit set, size and marketability. Many fruit crops depend on animal pollination, and wild pollinators in particular often increase fruit set and quality even when honey bees are present (Klein et al., 2007; Garibaldi et al., 2013). Experimental work on strawberries shows that bee pollination improves fruit shape, firmness, shelf life and commercial grade, and wild bees can produce larger fruits than managed honey bees in some systems (Klatt et al., 2014; MacInnis & Forrest, 2019). In almonds and other nut/tree crops, field experiments demonstrate that bee visitation raises fruit set and kernel yield, so even "self-fertile" varieties benefit from pollinators (Sáez et al., 2020). For tropical fruits such as mango, field studies likewise report substantial contributions of insect visitors to fruit set and retention (Abdul Razak et al., 2015). Predators and parasitoids lower pest densities and so protect fruit appearance and marketability. Recent syntheses and meta-analyses find biological-control interventions reduce pest abundance and crop damage while maintaining natural-enemy communities (Ratto et al., 2022). Augmentative and conservation use of parasitoids such as Diachasmimorpha longicaudata has a long record of reducing fruit-fly populations in mango and citrus orchards (Montoya et al., 2000). Adopting IPM and biological control also markedly lowers insecticide use and pesticide residues without sacrificing yields, which supports food-safety goals and market access (Pecenka et al., 2021; Ratto et al., 2022). Together, pollinators plus predators/parasitoids both raise yield/quality and reduce reliance on chemicals, giving growers clear economic and phytosanitary benefits (Garibaldi et al., 2013; Pecenka et al., 2021).

Threats and Challenges to Beneficial Insects

The survival and functional effectiveness of beneficial insects in fruit agroecosystems are being eroded by a tight constellation of interacting anthropogenic and environmental stressors that together reduce pollination and biological control services; chief among these is widespread synthetic pesticide use, which although intended for pest suppression frequently causes lethal and sublethal harm to non-target natural enemies and pollinators — including lady beetles, parasitoid wasps, solitary and social bees, and hoverflies thereby undermining population viability and ecosystem function (Desneux et al., 2007; Johnson et al., 2010). Systemic neonicotinoids in particular have been robustly linked to impaired navigation, reduced foraging success, compromised colony performance and lower reproductive output in honey bees and bumble bees at field-realistic exposures, and field studies and meta-analyses have documented population and colony-level consequences consistent with those mechanistic effects (Cresswell, 2011; Goulson, 2013; Henry et al., 2012; Whitehorn et al., 2012; Rundlöf et al., 2015). Importantly, the real-world toxic burden

experienced by beneficials in orchards is rarely a single-compound exposure: mixes of insecticides and fungicides commonly used in the same spray programs can interact synergistically to magnify harm to natural enemies and pollinators beyond single-compound expectations (Desneux et al., 2007; Johnson et al., 2010). At the landscape and management scale, agricultural intensification conversion of diverse habitats to large monocultures, loss of hedgerows and semi-natural vegetation, and intensified tillage strips floral resources and nesting sites, reduces species richness and functional diversity, and weakens resilience of pollinator and natural-enemy communities needed for stable pollination and biological control (Kennedy et al., 2013; Ricketts, 2004; Potts et al., 2010). Climate change compounds these pressures by shifting temperature and precipitation regimes and causing phenological mismatch between crop flowering and pollinator activity and by altering seasonal abundance and range distributions of beneficial insects (Kudo & Ida, 2013; Potts et al., 2010), while invasive pests such as *Drosophila suzukii* disrupt local food webs and complicate biological-control efforts by competing with or otherwise altering interactions among native natural enemies and parasitoids (Asplen et al., 2015).

Equally important are indirect and biological stressors that interact with the above drivers to amplify declines in beneficial insects in fruit systems. Genetically engineered Bt crops have reduced some pesticide applications and, on aggregate, short-term direct lethal effects of Bt Cry proteins on many non-target taxa appear limited in meta-analyses, but indirect effects via altered insecticide regimes, changes in crop and field floral composition, and long-term landscape homogenization remain causes for caution (Duan et al., 2008; Marvier et al., 2007). Infectious agents and parasites for example *Nosema ceranae* and viruses vectored by *Varroa* spp. interact with chemical stressors and nutritional or habitat deficits to elevate colony mortality and weaken pollinator populations (Van der Zee et al., 2012; Potts et al., 2010). Compounding these biological and chemical pressures are socio-economic and governance shortfalls limited farmer awareness of pollinator-friendly practices, insufficient enforcement of protective measures, and patchy monitoring of beneficial-insect diversity in orchards which delay detection and response; together these findings argue for integrated solutions that reduce unnecessary pesticide use, restore and connect semi-natural habitats and floral resources, incorporate climate-resilient management, require rigorous ecological risk assessment before releasing exotic biocontrol agents, and strengthen farmer education and monitoring programs to sustain pollination and biological control services in fruit cropping systems (Kennedy et al., 2013; Potts et al., 2010; Johnson et al., 2010).

Habitat Management and conservative strategies for Promoting Beneficial Insects

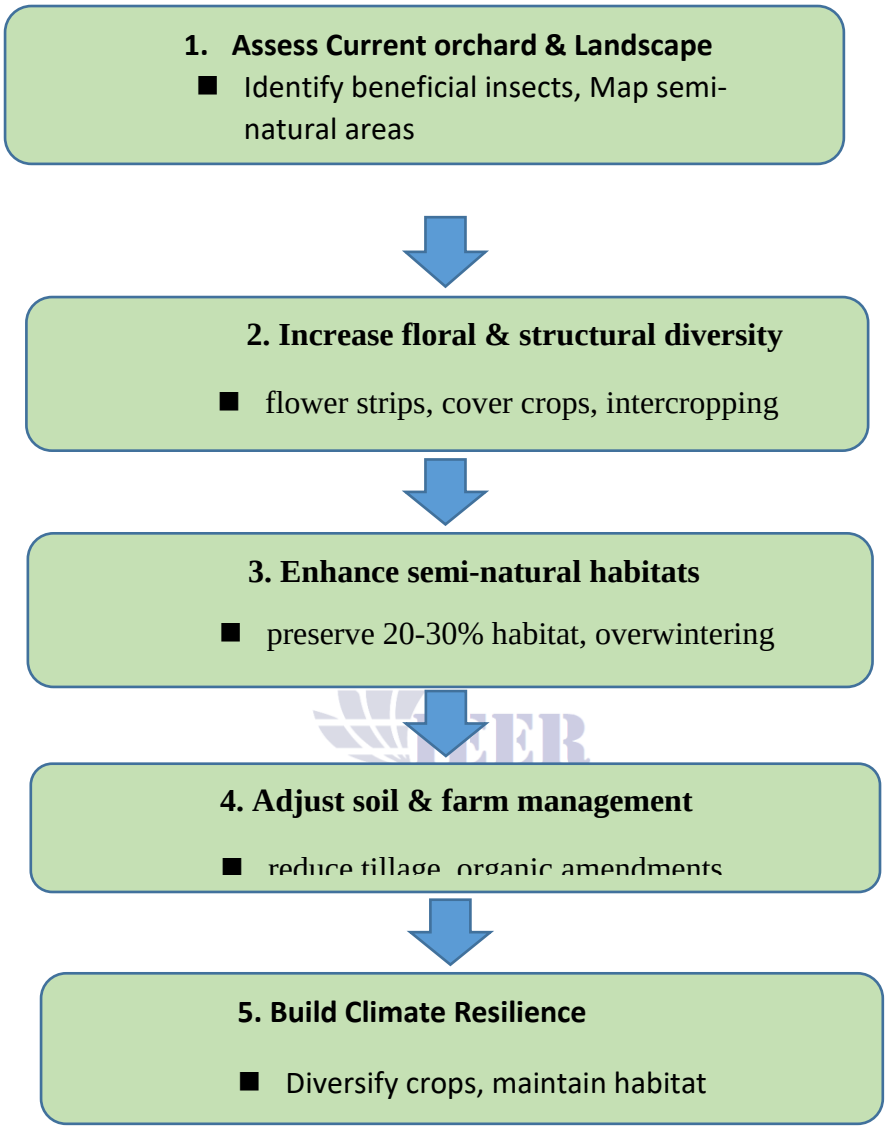
One of the most effective ecological instruments that contemporary fruit growers can utilise to conserve and enhance useful insect species is habitat management. Pollinators, predators and parasitoids are all vital to crop production and pest regulation, but agricultural intensification and monoculture practices have driven widespread habitat loss and fragmentation, making targeted habitat-management approaches an essential component of ecologically sound orchard systems (Landis et al., 2000; Gurr et al., 2017). By introducing structural and floral elements such as hedgerows, flower strips, field margins, cover crops and intercropping systems, farmers can create more biodiverse environments that align with the life cycles and functional roles of beneficial insects (Tscharntke et al., 2005). Flowering strips planted among or between orchard rows provide continuous access to nectar and pollen when the main crop is not in bloom, supporting pollinators such as bees and hoverflies as well as natural enemies like parasitic wasps and predatory beetles (Tschumi et al., 2016). Floral strips and adjacent wildflower plantings have been shown to increase pollinator and natural-enemy abundance in multiple crops (for example, adjacent highbush blueberry fields; Blaauw & Isaacs, 2014), and experimental trials have documented rises in hoverfly and parasitoid numbers with associated reductions in herbivore pressure (Tschumi et al., 2016). Intercropping and cover-crop approaches similarly increase the habitat complexity that supports predators (including lady beetles, spiders,

and other generalist enemies); a recent systematic review and meta-analysis reports that intercropping broadly enhances beneficial arthropods and can reduce pest abundance relative to monocultures (Rakotomalala et al., 2023). Semi-natural habitats surrounding orchards are positively associated with improved pest management and pollination services at the landscape scale (Kennedy et al., 2013); these areas provide overwintering and nesting sites for ground-dwelling beetles, solitary bees and other invertebrates that help regulate local ecosystem processes (Snyder, 2019). While some syntheses report that landscapes with roughly 20–30% semi-natural habitat tend to show substantially higher bee richness and visitation than heavily simplified landscapes, that threshold is context- and scale-dependent and can vary with crop and regional landscape structure (Dainese et al., 2019).

Soil and farm-management practices further influence habitat quality for beneficial insects. Reduced tillage and incorporation of organic amendments improve soil structure, promote aggregation and increase detritivore and ground-predator richness, thereby supporting more stable and efficient food webs (Six et al., 2004; Hole et al., 2005). Systems that limit or exclude synthetic pesticides (e.g., many organic systems) consistently show higher insect biodiversity, including beneficial taxa such as hoverflies, lacewings and parasitic wasps (Hole et al., 2005). Cover crops and composted mulches serve as microhabitats that retain moisture and provide shelter, boosting survivorship of ground-dwelling beneficials during adverse weather. Timing and local adaptation of habitat interventions are crucial: flowering strips should be designed to synchronise with the phenology of pollinators and natural enemies so that resources are available throughout the season (Tschumi et al., 2015), and edge habitats such as hedgerows should be managed to avoid becoming reservoirs for pest species. Effective habitat manipulation is best developed in partnership with farmers, agronomists and entomologists (Wyckhuys et al., 2013), and practical innovations such as artificial nesting structures and bee hotels can enhance solitary-bee nesting and pollination services when implemented with ecological guidance (MacIvor & Packer, 2015). Finally, habitat management contributes to climate resilience: diversified orchards and connected semi-natural habitats provide functional redundancy and insect-guild diversity that buffer pollination and pest-regulation services against phenological shifts and pest range changes driven by climate variation (Tamburini et al., 2020; Garibaldi et al., 2014). These practices also tend to reduce synthetic input needs and lower production costs, supporting long-term sustainability; overall, habitat management in fruit orchards is not merely about increasing insect numbers but about integrating ecological design into productive systems so that flowering strips, cover crops, reduced tillage and preservation of semi-natural landscapes together sustain resilient, high-yield and environmentally friendly fruit production (Gurr et al., 2017; Landis et al., 2000).

Fig no. 1. Habitat Management

Fig no. 1. Habitat Management



Integration of Beneficial Insects in Integrated Pest Management (IPM)

Integrated Pest Management (IPM) emphasizes the use of environmentally and economically sustainable approaches to reduce pest populations, with beneficial insects playing a central role in these systems. Predators, parasitoids, and pollinators are integrated into IPM programs to suppress pest outbreaks while minimizing reliance on chemical pesticides. In fruit crops such as citrus, apples, and grapes, natural enemies like *Trichogramma* spp. (egg parasitoids), *Aphidius colemani* (aphid parasitoid), *Chrysoperla carnea* (green lacewing), and predatory mites have demonstrated effective suppression of key pests without significantly affecting non-target organisms (Stenberg, 2017; van Lenteren et al., 2018). The compatibility of beneficial insects with selective pesticides and cultural practices allows them to be incorporated flexibly into management plans. Maintaining pollinator populations within IPM frameworks is equally important; practices such as reducing insecticide applications during

flowering, using bee-safe products, and establishing flowering ground covers help sustain pollinator abundance and diversity, which in turn supports fruit set and quality (Garibaldi et al., 2014; Eeraerts et al., 2020). The incorporation of flowering strips, hedgerows, and cover crops has been shown to increase the diversity and activity of natural enemies, leading to pest suppression before economic thresholds are reached (Tschumi et al., 2016; Albrecht et al., 2020).

The use of beneficial insects in IPM also contributes to long-term agricultural sustainability. By reducing pesticide use, these biological control agents help slow the development of pest resistance, lower production costs, and maintain biodiversity at the field and landscape scale. Studies in orchards and vineyards have shown that predatory mites and spiders can maintain thrips, leafhoppers, and mite pests at sub-economic levels, while augmentative releases of parasitoids such as *Diachasmimorpha longicaudata* have effectively controlled fruit flies in citrus and mango systems (Vargas et al., 2015; Thomson & Hoffmann, 2013). Farmers adopting insect-based IPM often report increased yields and improved market returns, particularly for pesticide-free or residue-compliant produce, which is in demand in high-value export markets. Education, farmer training, and extension services are critical to optimizing the use of beneficial insects, ensuring growers are equipped to identify key species, monitor pest and beneficial populations, and choose interventions that favor ecosystem services (Parsa et al., 2014; Gurr et al., 2017). When implemented effectively, IPM that integrates beneficial insects not only safeguards crop productivity but also supports the ecological integrity of orchard systems.

Knowledge Gaps and Research Needs

Despite substantial advances in understanding the role of beneficial insects in sustainable fruit production, significant knowledge gaps remain that limit effective conservation and integration into orchard management. One major gap is the lack of long-term, multi-season studies that measure both ecological and economic outcomes of beneficial insect use, particularly in diverse climatic zones and under varying management intensities (Isaacs et al., 2009). Many studies focus on short-term pest suppression or pollination benefits, but fewer quantify cumulative effects on yield stability, fruit quality, and farm profitability over time. Another limitation is the geographic bias in research, with much of the evidence coming from Europe and North America, while tropical and subtropical fruit systems remain underrepresented despite their high biodiversity and dependence on insect-mediated services (Garibaldi et al., 2013). There is also a need to better understand species-specific interactions, such as competition or facilitation among native and introduced pollinators and predators, as well as the indirect effects of climate change on insect phenology and behavior (Rader et al., 2016). Methodological gaps persist in linking landscape-scale habitat management to orchard-level outcomes, particularly in quantifying how floral strips, hedgerows, and reduced tillage interact with surrounding land use to influence beneficial insect populations (Blaauw & Isaacs, 2014). Furthermore, socio-economic research is often disconnected from ecological studies, meaning adoption barriers, farmer perceptions, and cost-benefit analyses are insufficiently integrated into conservation strategies. Addressing these gaps will require interdisciplinary research that combines ecological monitoring, economic modeling, and participatory approaches with growers to co-develop scalable, context-specific interventions.

Practical Recommendations for Growers

To support beneficial insects in orchards, growers should adopt habitat enhancements, selective pest control, and supportive farming practices. Planting perennial flower strips, hedgerows, and cover crops near fruit trees provides year-round floral resources and safe refuges for pollinators and natural enemies (Albrecht et al., 2020). Including native flowering species improves compatibility with local beneficials and reduces maintenance. Introducing artificial nesting structures, such as well-designed bee hotels or nest blocks, can increase cavity-nesting bee populations like Osmia spp., especially when materials are maintained to prevent overcrowding or disease (Rahimi et al., 2021). When managing pests, replacing broad-spectrum insecticides with microbial or botanical biopesticides such as Bacillus

thuringiensis and timing sprays to avoid bloom and peak insect activity helps preserve beneficial diversity (Torres & Bueno, 2018; Ayilara et al., 2023). Minimizing tillage and maintaining ground cover supports soil-dwelling predators and maintains soil health, which aids in pest suppression and root function (Müller et al., 2022; Meurer et al., 2020). Effective implementation depends on farmer knowledge and incentives; extending targeted trainings, demonstration plots, and linking practices to market premiums for low-residue produce or ecosystem service outcomes boost adoption (Hagemann et al., 2024). By combining habitat creation, selective chemistries, soil-friendly practices, and grower support, fruit producers can maintain high levels of ecosystem services while reducing chemical dependencies.

Conclusion

The integration of beneficial insects into sustainable fruit production offers a practical, ecologically sound alternative to heavy chemical reliance. By combining habitat enhancement, selective pest control, and supportive farm management, growers can maintain pollination services, suppress pests naturally, and improve overall ecosystem resilience (Garibaldi et al., 2020; Albrecht et al., 2020). Long-term success depends not only on technical measures but also on farmer knowledge, socio-economic incentives, and supportive policies, which together foster adoption at scale (Kleijn et al., 2019). Research indicates that such systems can deliver equal or higher yields compared to conventional methods, while reducing input costs and preserving biodiversity (Dainese et al., 2019; Gagic et al., 2021). Nevertheless, challenges remain, including region-specific pest dynamics, climate variability, and gaps in understanding how multiple beneficial insect guilds interact under diverse orchard conditions. Addressing these will require targeted research, participatory extension, and adaptive management that blends ecological knowledge with local farming realities. With coordinated effort from scientists, policymakers, and growers, beneficial insect–based strategies can become a cornerstone of climate-resilient, economically viable, and biodiversity-friendly fruit production systems.

References

Abbas, M., Hussain, D., Saleem, M., Ghaffar, A., Abbas, S., Hussain, N., & Ghaffar, A. (2021). Integrated pest management of guava, citrus and mango fruitflies at three districts of Punjab. *Pakistan Journal of Zoology*, *53*(3), 995.

Abdul Razak, A., et al. (2015). Pollination services of mango flower pollinators. *Journal of Insect Science*, *15*(1), 113. https://doi.org/10.1093/jisesa/iev090

Ahmad, T., Ahmad, B., & Mahmood, H. Z. (2023, May). Status of horticulture sector in Pakistan. Presented at the Second International Conference on Horticulture, Nepal. Speaker upload.https://www.researchgate.net/publication/376135317_Status_of_Horticulture_Sector_in_Pakistan

Albrecht, M., Kleijn, D., Williams, N. M., Tschumi, M., Blaauw, B. R., Bommarco, R., ... & Wäckers, F. (2020). The effectiveness of flower strips and hedgerows on pest control, pollination services and crop yield: a quantitative synthesis. *Ecology Letters*, 23(10), 1488–1498. https://doi.org/10.1111/ele.13576

Al-Dosary, N.M., Al-Dobai, S., & Faleiro, J.R. (2016). Review on the management of red palm weevil Rhynchophorus ferrugineus Olivier in date palm. *Emirates Journal of Food and Agriculture*, 28(1), 34–44.

Ali, M., Sajjad, A., Farooqi, M. A., Bashir, M. A., Aslam, M. N., Nafees, M., ... & Khan, K. A. (2020). Assessing indigenous and local knowledge of farmers about pollination services in cucurbit agro-ecosystem of Punjab, Pakistan. *Saudi Journal of Biological Sciences*, *27*(1), 189–194. https://doi.org/10.1016/j.sjbs.2019.07.001

Al-Shawaf, A.M., Al-Hajhoj, M.R., & Al-Yahya, F.A. (2013). Field evaluation of *Trichogramma evanescens* Westwood (Hymenoptera: Trichogrammatidae) against the lesser date moth *Batrachedra amydraula* in Saudi Arabia. *Journal of Entomology*, 10(1), 1–8.

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, 35(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2

Anderson, D. J., Berson, J. D., Didham, R. K., Simmons, L. W., & Evans, T. A. (2024). Dung beetles increase plant growth: a meta-analysis. *Proceedings of the Royal Society B: Biological Sciences, 291*(2019), 20232885. https://doi.org/10.1098/rspb.2023.2885.

Anees, M., Ali, M., Ghramh, H. A., Sajjad, A., Khan, K. A., Saeed, S., & Razzaq, K. (2022). Impact of bee and fly pollination on physical and biochemical properties of strawberry fruit. *Horticulturae, 8*(11), 1072. https://doi.org/10.3390/horticulturae8111072

Asplen, M. K., Anfora, G., Biondi, A., Choi, D.-S., Chu, D., Daane, K. M., Gibert, P., Gutierrez, A. P., Hoelmer, K. A., Hutchison, W. D., Isaacs, R., Jiang, Z., Karpati, Z., Kimura, M. T., Pascual, M., Phillips, C. R., Plantamp, C., Ponti, L., Vétek, G., Vogt, H., Walton, V. M., Yu, Y., Zappalà, L., & Desneux, N. (2015). Invasion biology of spotted wing *Drosophila* (*Drosophila suzukii*): a global perspective and future priorities. *Journal of Pest Science*, *88*(3), 469–494. https://doi.org/10.1007/s10340-015-0681-z

Associated Press of Pakistan. (2025, July 28). *Experts call for urgent reform of agricultural subsidies to combat environmental damage*. APP National News Service. https://www.app.com.pk/national/experts-call-for-urgent-reform-of-agricultural-subsidies-to-combat-environmental-damage/

Ayilara, M. S., Adeleke, B. S., Akinola, S. A., Fayose, C. A., Adeyemi, U. T., Gbadegesin, L. A., … Babalola, O. O. (2023). Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides. *Frontiers in Microbiology, 14*, Article 1040901. https://doi.org/10.3389/fmicb.2023.1040901

Aziz, S. S., & Hussain, M. (2018). Fruit pest management in Pakistan. *Scientific Inquiry and Review*, *2*(4), 43-52.

Bakhtawer, A., & Afsheen, S. (2021). A cross sectional survey of knowledge, attitude and practices related to the use of insecticides among farmers in industrial triangle of Punjab, Pakistan. *PLOS ONE, 16*(8), e0255454. https://doi.org/10.1371/journal.pone.0255454

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., … & Cardinael, R. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. *Nature Communications*, *14*(1), 3700.

Bengtsson, J., Ahnström, J., & Weibull, A. C. (2005). The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *Journal of Applied Ecology, 42*(2), 261–269. https://doi.org/10.1111/j.1365-2664.2005.01005.x.

Blaauw, B. R., & Isaacs, R. (2014). Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *Journal of Applied Ecology, 51*(4), 890–898. https://doi.org/10.1111/1365-2664.12257

Brown, G.G., Barois, I., & Lavelle, P. (2010). Regulation of soil organic matter dynamics and microbial activity in the drilosphere. *European Journal of Soil Biology*, 36(3), 177-198.

Cheema, I. A., & Jamali, H. K. (2020). Growth of citrus fruits in Pakistan. *Amazonia Investiga*, *9*(35), 74–81.

Cresswell, J. E. (2011). A meta-analysis of experiments testing the effects of a neonicotinoid insecticide (imidacloprid) on honey bees. *Ecotoxicology*, *20*(1), 149–157. https://doi.org/10.1007/s10646-010-0566-0

Dabholkar, S., Pirani, S., Davis, M., Khan, M., & Eddleston, M. (2023). Suicides by pesticide ingestion in Pakistan and the impact of pesticide regulation. *BMC public health*, *23*(1), 676.

Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., ... & Steffan-Dewenter, I. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, *5*(10), eaax0121. https://doi.org/10.1126/sciadv.aax0121

Davidson, A. P., Ahmed, M., & Ali, T. (2001). Dilemmas of agricultural extension in Pakistan: Food for thought. Network Paper# 116. *Agric. Res. & Ext. Network. Retrieved: March*, *13*, 2005.

Desneux, N., Decourtye, A., & Delpuech, J.-M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, *52*, 81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440

Duan, J. J., Marvier, M., Huesing, J., Dively, G., & Huang, Z. Y. (2008). A meta-analysis of effects of Bt crops on honey bees (Hymenoptera: Apidae). *PLoS ONE*, *3*(1), e1415. https://doi.org/10.1371/journal.pone.0001415

Eeraerts, M., Vanderhaegen, R., Smagghe, G., & Meeus, I. (2020). Pollinator diversity, floral resources and semi-natural habitat, instead of honey bees and intensive agriculture, enhance pollination service to seed set in oilseed rape. *Agriculture, Ecosystems & Environment*, 291, 106794. https://doi.org/10.1016/j.agee.2019.106794

FAO. 2022. *Statistical Yearbook: World Food and Agriculture*. Food and Agriculture Organization of the United Nations, Rome, Italy. Available at: https://www.fao.org/statistics/yearbook

Food and Agriculture Organization. (2023). *Pesticides use and trade 1990–2022*. FAO. Retrieved from https://www.fao.org/statistics/highlights-archive/highlights-detail/pesticides-use-and-trade-1990-2022/en

Gagic, V., Kleijn, D., Báldi, A., Boros, G., Jørgensen, H. B., Elek, Z., ... Bommarco, R. (2021). Combined effects of agrochemicals and ecosystem services on crop yield across Europe. *Ecology Letters*, *24*(12), 2736–2747. https://doi.org/10.1111/ele.13899

Garibaldi, L. A., Carvalheiro, L. G., Leonhardt, S. D., Aizen, M. A., Blaauw, B. R., Isaacs, R., ... & Klein, A. M. (2014). From research to action: enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment*, 12(8), 439–447. https://doi.org/10.1890/130330

Garibaldi, L. A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., ... Klein, A. M. (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, *339*(6127), 1608–1611. https://doi.org/10.1126/science.1230200

Goulson, D. (2013). An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, *50*(4), 977–987. https://doi.org/10.1111/1365-2664.12111

Gross, K., & Rosenheim, J. A. (2011). Quantifying secondary pest outbreaks in cotton and their monetary cost with causal-inference statistics. *Ecological Applications, 21*(7), 2770–2780. https://doi.org/10.1890/11-0118.1

Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. (2017). Habitat management to suppress pest populations: Progress and prospects. *Annual Review of Entomology*, 62, 91–109. https://doi.org/10.1146/annurev-ento-031616-035050

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., ... & Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science advances*, *1*(2), e1500052.

Hagemann, N., Gerling, C., Hölting, L., Kernecker, M., Markova-Nenova, N. N., Wätzold, F., ... & Cord, A. F. (2025). Improving result-based schemes for nature conservation in agricultural landscapes—challenges and best practices from selected European countries. *Regional Environmental Change*, *25*(1), 12.

Hagler, J.R., & Daane, K.M. (1998). Parasitoids, predators, and pathogens of glassy-winged sharpshooter. *Entomological News*, 109(5), 339–344.

Hebert, P.D.N., Cywinska, A., Ball, S.L., & deWaard, J.R. (2003). Biological identifications through DNA barcodes. *Proceedings of the Royal Society B*, 270(1512), 313-321.

Henry, M., Béguin, M., Requier, F., Rollin, O., Odoux, J.-F., Aupinel, P., Aptel, J., Tchamitchian, S., & Decourtye, A. (2012). A common pesticide decreases foraging success and survival in honey bees. *Science*, *336*(6079), 348–350. https://doi.org/10.1126/science.1215039

Hole, D. G., Perkins, A. J., Wilson, J. D., Alexander, I. H., Grice, P. V., & Evans, A. D. (2005). Does organic farming benefit biodiversity? *Biological Conservation, 122*(1), 113–130. https://doi.org/10.1016/j.biocon.2004.07.018.

Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstic, D., ... & El-Esawi, M. A. (2021). Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage. *Plants*, *10*(10), 2001.

Javaid, Z., Ghazala, Ibrahim, M., Mahmood, A., & Bajwa, A. A. (2023). Pesticide contamination of potable water and its correlation with water quality in different regions of Punjab, Pakistan. *Water, 15*(3), 543. https://doi.org/10.3390/w15030543

Johnson, R. M., Ellis, M. D., Mullin, C. A., & Frazier, M. (2010). Pesticides and honey bee toxicity – USA. *Apidologie*, *41*(3), 312–331. https://doi.org/10.1051/apido/2010018

Jonsson, M., Wratten, S. D., Landis, D. A., & Gurr, G. M. (2008). Recent advances in conservation biological control of arthropods by arthropods. Biological Control, 45(2), 172–175

Jan, A., Shaikh, G. Y., Ullah, S., Saddam, S., Ali, T., u Rehman, A., ... & Ahmed, M. (2025). In-vitro Antifungal Activity of Medicinal Plant Extracts against Fusarium oxysporum Causing Wilt in Okra. Indus Journal of Bioscience Research, 3(8), 406-414.

Jan, A., Adil, S., Ali, T., Ahmed, B., Ahmed, Z., & Hussain, Z. (2025). Desert and Medicinal Plants as Novel Sources of Antimicrobial Agents for Crop Protection. Planta Animalia, 4(3), 197-218.

Jan, A., Ali, T., Chirag, S., Ahmed, S., Ali, M., Wali, S., Basit, A., Ibrahim, M., & Ullah, K. (n.d.). Eco-Friendly Management of Insect Pests and Plant Diseases Using Botanical Extracts. Global Research Journal of Natural Science and Technology.

Kakade, A. M., Sharma, R. R., & Singh, D. (2021). Integrated management of mango mealybug (Drosicha mangiferae Green): A review. Indian Journal of Entomology, 83(1), 8–18.

Kennedy, C. M., Lonsdorf, E., Neel, M. C., Williams, N. M., Ricketts, T. H., Winfree, R., Bommarco, R., Brittain, C., Burley, A. L., Cariveau, D., Carvalheiro, L. G., Chacoff, N. P., Cunningham, S. A., Danforth, B. N., Dudenhöffer, J.-H., Elle, E., Gaines, H. R., Garibaldi, L. A., Gratton, C., … Kremen, C. (2013). A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters*, *16*(5), 584–599. https://doi.org/10.1111/ele.12082

Khan, A. A., Shah, M. A., & Rahman, S. U. (2013). Occupational exposure to pesticides and its effects on health status of workers in Swat, Khyber Pakhtunkhwa, Pakistan. *Journal of Biology and Life Sciences*, *4*(2), 43. https://doi.org/10.5296/jbls.v4i2.3777

Khan, M. A., Akbar, M., Ahmad, S., & Ali, S. (2001). Determination of fruit flies (Diptera: Tephritidae) infestation in guava, peach, and bitter gourd orchards in Khyber Pakhtunkhwa. Pakistan Journal of Biological Sciences, 4(2), 157–159.

Khan, M.A., Nasir, M., & Arif, M.J. (2015). Mass rearing of *Chrysoperla carnea* for biological control of citrus pests. *Journal of Agricultural Research*, 53(2), 233–239.

Klatt, B. K., Holzschuh, A., Westphal, C., Clough, Y., & Tscharntke, T. (2014). Bee pollination improves crop quality, shelf life and commercial value. *Proceedings of the Royal Society B: Biological Sciences, 281*, 20132440. https://doi.org/10.1098/rspb.2013.2440

Kleijn, D., Winfree, R., Bartomeus, I., Carvalheiro, L. G., Henry, M., Isaacs, R., … Potts, S. G. (2019). Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Communications, 10*, 2687. https://doi.org/10.1038/s41467-019-08541-3

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B, 274*(1608), 303–313. https://doi.org/10.1098/rspb.2006.3721

Kudo, G., & Ida, T. Y. (2013). Early onset of spring increases the risk of phenological mismatch between plants and pollinators. *Ecology*, *94*(10), 2311–2320. https://doi.org/10.1890/12-2003.1

Landis, D. A., Wratten, S. D., & Gurr, G. M. (2000). Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology, 45*, 175–201. https://doi.org/10.1146/annurev.ento.45.1.175

Larsen, T.H., Williams, N.M., & Kremen, C. (2005). Extinction order and altered community structure rapidly disrupt ecosystem functioning. *Ecology Letters*, 8(5), 538–547.

Li, L.Y. (2014). Worldwide use of *Trichogramma* for biological control on different crops: a survey. In *Biological Control with Egg Parasitoids* (pp. 37–53). CAB International.

Liu, R., & Yang, B. (2023). Editorial: Soil microbe-arthropod interactions under global change. *Frontiers in Microbiology, 14*, Article 1280103. https://doi.org/10.3389/fmicb.2023.1280103

Luo, B., Huang, M., Wang, W., Niu, J., Shrestha, M., Zeng, H., Ma, L., Degen, A. A., Liao, J., Zhang, T., Bai, Y., Zhao, J., Fraser, L. H., & Shang, Z. (2023). Ant nests increase litter decomposition to mitigate the negative effect of warming in an alpine grassland ecosystem. *Proceedings of the Royal Society B: Biological Sciences, 290*(2001), 20230613. https://doi.org/10.1098/rspb.2023.0613.

MacInnis, G., & Forrest, J. R. K. (2019). Pollination by wild bees yields larger strawberries than pollination by honey bees. *Journal of Applied Ecology, 56*(4), 824–833. https://doi.org/10.1111/1365-2664.13344

MacIvor, J. S., & Packer, L. (2015). "Bee hotels" as tools for native pollinator conservation: A premature verdict? *PLOS ONE, 10*(3), e0122126. https://doi.org/10.1371/journal.pone.0122126

Mahmood, M. A., Ahmed, N., Hussain, S., Muntaha, S. T., Amin, I., & Mansoor, S. (2022). Dominance of Asia II 1 species of *Bemisia tabaci* in Pakistan and beyond. *Scientific Reports, 12*, 1528. https://doi.org/10.1038/s41598-022-05612-1

Mahmood, R., Aslam, M., & Razaq, M. (2021). Field efficacy of indigenous parasitoids against pomegranate butterfly. BioControl, 66(4), 487–498. https://doi.org/10.1007/s10526-021-10097-4

Marvier, M., McCreedy, C., Regetz, J., & Kareiva, P. (2007). A meta-analysis of effects of Bt cotton and maize on non-target invertebrates. *Science, 316*(5830), 1475–1477. https://doi.org/10.1126/science.1139208

Masood, N., Akram, R., Fatima, M., Mubeen, M., Hussain, S., Shakeel, M., ... & Nasim, W. (2021). Insect pest management under climate change. In *Building climate resilience in agriculture: Theory, practice and future perspective* (pp. 225-237). Cham: Springer International Publishing.

Meena, P. N., Raghavendra, D., Singh, S., Kumar, N., Khokhar, M. K., Chander, S., ... & Kumar, R. (2025). Integrated Pest Management techniques in a Kinnow mandarin (Citrus reticulata Blanco) orchard with an emphasis on yield improvement. *Heliyon, 11*(4).

Meurer, K., Barron, J., Chenu, C., Coucheney, E., Fielding, M., ... Jarvis, N. (2020). A framework for modelling soil structure dynamics induced by biological activity. *Global Change Biology, 26*(10), 5382–5403. https://doi.org/10.1111/gcb.15289

Meyerdirk, D.E., Warkentin, R., & Attavian, A. (2001). Biological control of the pink hibiscus mealybug, *Maconellicoccus hirsutus* (Hemiptera: Pseudococcidae). *Integrated Pest Management Reviews*, 6(4), 293–300.

Ministry of Commerce. (2023). Pakistan export strategy Fruits and vegetables. Government of Pakistan.https://www.commerce.gov.pk/wpcontent/uploads/2024/05/Fruits_and_Vegetable_sector_strategy-Pakistan-3_web.pdf

Montoya, P., Liedo, P., Benrey, B., Cancino, J., Barrera, J. F., Sivinski, J., & Aluja, M. (2000). Biological control of *Anastrepha* spp. (Diptera: Tephritidae) in mango orchards through augmentative releases of *Diachasmimorpha longicaudata* (Ashmead) (Hymenoptera: Braconidae). *Biological Control, 18*(3), 216–224. https://doi.org/10.1006/bcon.2000.0819

Müller, P., Neuhoff, D., Nabel, M., Schiffers, K., & Döring, T. F. (2022). Tillage effects on ground beetles in temperate climates: A review. *Agronomy for Sustainable Development, 42*, Article 65. https://doi.org/10.1007/s13593-022-00803-6

Nafees, M. N., Jan, M. R., & Khan, H. K. (2008). Pesticide use in Swat Valley, Pakistan: Exploring remedial measures to mitigate environmental and socioeconomic impacts. *Mountain Research and Development, 28*(3–4), 201–204. https://doi.org/10.1659/mrd.0951

Nicholls, C. I., & Altieri, M. A. (2004). Designing species-rich, pest-suppressive agroecosystems through habitat management. *Agroecosystems analysis*, *43*, 49-61.

Noman, H., Saif, S., & Shoukat, S. (2024). *Sustainable pest management strategies for agriculture in Pakistan: A review.* Plant Protection, 8(4), 789–802. https://doi.org/10.33804/pp.008.04.5386.

Obrycki, J. J., & Kring, T. J. (1998). Predaceous Coccinellidae in biological control. *Annual Review of Entomology, 43*, 295–321. https://doi.org/10.1146/annurev.ento.43.1.295.

Otieno, M. M. O. (2021). A review of white mango scale (*Aulacaspis tubercularis* Newstead; Hemiptera: Diaspididae) in Sub-Saharan Africa: distribution, impact and management strategies. *Pakistan Journal of Agricultural Research, 34*(1), 227–238.

Parsa, S., Morse, S., Bonifacio, A., Chancellor, T. C., Condori, B., Crespo-Pérez, V., ... & Dangles, O. (2014). Obstacles to integrated pest management adoption in developing countries. *Proceedings of the National Academy of Sciences*, 111(10), 3889–3894. https://doi.org/10.1073/pnas.1312693111

Pecenka, J. R., Ingwell, L. L., Foster, R. E., Krupke, C. H., & Kaplan, I. (2021). IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation. *Proceedings of the National Academy of Sciences, 118*(44), e2108429118. https://doi.org/10.1073/pnas.2108429118

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W. E., & *et al.* (2010). Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, *25*(6), 345–353. https://doi.org/10.1016/j.tree.2010.01.007

Queirós, F., Carvalho, R., de Sousa, R., & Sánchez, C. (2023, May). Insect pollination improves fruit set, yield and fruit quality of commercial sweet cherry. In *IX International Cherry Symposium 1408* (pp. 267-274).

Rader, R., Bartomeus, I., Garibaldi, L. A., Garratt, M. P., Howlett, B. G., Winfree, R., ... & Woyciechowski, M. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences, 113*(1), 146–151. https://doi.org/10.1073/pnas.1517092112

Rahimi, E., Barghjelveh, S., & Dong, P. (2021). How effective are artificial nests in attracting bees? A review. *Journal of Ecology and Environment, 45*, Article 16. https://doi.org/10.1186/s41610-021-00192-z

Rakotomalala, A. A. N. A., Ficiciyan, A. M., & Tscharntke, T. (2023). Intercropping enhances beneficial arthropods and controls pests: A systematic review and meta-analysis. *Agriculture, Ecosystems & Environment, 356*, 108617. https://doi.org/10.1016/j.agee.2023.108617

Ratto, F., Bruce, T. J. A., Chipabika, G., Mwamakamba, S., Mkandawire, R., Khan, Z., ... Sait, S. M. (2022). Biological control interventions reduce pest abundance and crop damage while maintaining natural enemies: a meta-analysis. *Proceedings of the Royal Society B, 289*, 20221695. https://doi.org/10.1098/rspb.2022.1695

Reemer, M., & Rotheray, G. E. (2009). Pollen-feeding larvae in the presumed predatory syrphine genus *Toxomerus* Macquart (Diptera, Syrphidae). *Journal of Natural History, 43*(15–16), 939–949. https://doi.org/10.1080/00222930802610576.

Reig, C., Martínez-Fuentes, A., & Agustí, M. (2015). Citrus pests. In M. Talon, M. Caruso, & F. G. Gmitter Jr. (Eds.), The Genus Citrus (pp. 153–171).

Ricketts, T. H. (2004). Tropical forest fragments enhance pollinator activity in nearby coffee crops. *Conservation Biology*, *18*(5), 1262–1271. https://doi.org/10.1111/j.1523-1739.2004.00227.x

Riddick, E. W., & Mills, N. J. (1994). Potential of adult carabids (Coleoptera: Carabidae) as predators of fifth-instar codling moth (Lepidoptera: Tortricidae) in apple orchards in California. *Environmental Entomology, 23*(5), 1338–1345. https://doi.org/10.1093/ee/23.5.1338.

Rundlöf, M., Andersson, G. K., Bommarco, R., Fries, I., Hederström, V., Herbertsson, L., ... & Smith, H. G. (2015). Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature*, *521*(7550), 77-80.

saacs, R., Tuell, J., Fiedler, A., Gardiner, M., & Landis, D. (2009). Maximizing arthropod-mediated ecosystem services in agricultural landscapes: The role of native plants. *Frontiers in Ecology and the Environment, 7*(4), 196–203. https://doi.org/10.1890/080035

Sáez, A., Aizen, M. A., Medici, S., Viel, M., Villalobos, E., & Negri, P. (2020). Bees increase crop yield in an alleged pollinator-independent almond variety. *Scientific Reports, 10*, 3177. https://doi.org/10.1038/s41598-020-59995-0

Sánchez-Bayo, F. (2021). Indirect effect of pesticides on insects and other arthropods. *Toxics, 9*(8), 177. https://doi.org/10.3390/toxics9080177

Sani, I., Ismail, S. I., Abdullah, S., Jalinas, J., Jamian, S., & Saad, N. A. (2020). A review of the biology and control of whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae), with special reference to biological control using entomopathogenic fungi. *Insects, 11*(9), 619. https://doi.org/10.3390/insects11090619

Shah, M. H., Rafique, R., Almas, M., Usman, M., Yasin, S., & Bibi, S. (2022). A review: Fruit production industry of Pakistan — trends, issues and way forward. *Pakistan Journal of Agricultural Research, 35*(3), 523–532. https://doi.org/10.17582/journal.pjar/2022/35.3.523.532

Sharma, S. K., Meena, R. L., & Bhati, A. (2017). Management of fruit flies (Diptera: Tephritidae) in fruit crops through eco-friendly approaches: A review. *Journal of Entomology and Zoology Studies, 5*(3), 1352–1356.

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research, 79*(1), 7–31. https://doi.org/10.1016/j.still.2004.03.008

Snyder, W. E. (2019). Give predators a complement: Conserving natural enemy biodiversity to improve biocontrol. *Biological Control, 135*, 73–82. https://doi.org/10.1016/j.biocontrol.2019.04.017.

Stenberg, J. A. (2017). A conceptual framework for integrated pest management. *Trends in Plant Science*, 22(9), 759–769. https://doi.org/10.1016/j.tplants.2017.06.010

Stocker, B., Barthold, S., & Betz, O. (2022). Mouthpart ecomorphology and predatory behaviour in selected rove beetles of the "Staphylinine group" (Coleoptera: Staphylinidae: Staphylininae, Paederinae). *Insects, 13*(8), 667. https://doi.org/10.3390/insects13080667.

Suhail, M. A., Arshad, M., Arif, J., & Gogi, M. D. (2010). Conservation of beneficial insects for sustainable agriculture. In H. Gökçekus, U. Türker, & J. LaMoreaux (Eds.), *Survival and Sustainability* (pp. 1435–1444). Springer. https://doi.org/10.1007/978-3-540-95991-5_137

Syed, T.S., Khan, A.A., & Khalid, S. (2022). Evaluation of *Chrysoperla carnea* and neem extract for control of mealybug in mango. *Pakistan Journal of Agricultural Sciences*, 59(2), 401–408.

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., van der Heijden, M. G., Liebman, M., & Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Science Advances*, *6*(45), eaba1715. https://doi.org/10.1126/sciadv.aba1715

Tariq, M. I., Afzal, S., Hussain, I., & Sultana, N. (2007). Pesticides exposure in Pakistan: A review. *Environment International*, *33*(8), 1107–1122. https://doi.org/10.1016/j.envint.2007.07.012

Thomson, L. J., & Hoffmann, A. A. (2013). Spatial scale of benefits from adjacent woody vegetation on natural enemies within vineyards. *Biological Control*, 64(1), 57–65.

Torres, J. B., & Bueno, A. D. F. (2018). Conservation biological control using selective insecticides—a valuable tool for IPM. *Biological Control*, *126*, 53–64. https://doi.org/10.1016/j.biocontrol.2018.07.012

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., & Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity–ecosystem service management. *Ecology letters*, *8*(8), 857-874.

Tschumi, M., Albrecht, M., Collatz, J., Dubsky, V., Entling, M. H., Najar-Rodriguez, A. J., & Jacot, K. (2016). Tailored flower strips promote natural enemy biodiversity and pest control in potato crops. *Journal of Applied Ecology*, 53(4), 1169–1176. https://doi.org/10.1111/1365-2664.12653

Tschumi, M., Albrecht, M., Entling, M. H., & Jacot, K. (2015). High effectiveness of tailored flower strips in reducing pests and crop damage in conventional cereal fields. *Proceedings of the Royal Society B*, *282*(1814), 20151369. https://doi.org/10.1098/rspb.2015.1369

Ullah, A., Saqib, S. E., & Kächele, H. (2022). Determinants of farmers' awareness and adoption of extension recommended wheat varieties in the rainfed areas of Pakistan. *Sustainability*, *14*(6), 3194.

Van der Zee, R., Pisa, L., Andonov, S., Brodschneider, R., Charrière, J.-D., Chlebo, R., Coffey, M. F., Dainat, B., de Miranda, J. R., Gajda, A., Genersch, E., Gogol-Döring, A., Hatjina, F., Korpela, S., Kristiansen, P., Lattorff, H. M. G., Meeus, I., Neumann, P., Özkök, R., ... de Renzis, G. (2012). Managed honey bee colony losses in Canada, China, Europe, Israel and Turkey, for the winters of 2008–9 and 2009–10. *Journal of Apicultural Research*, *51*(1), 100–114. https://doi.org/10.3896/IBRA.1.51.1.12

van Lenteren, J. C., Bolckmans, K., Köhl, J., Ravensberg, W. J., & Urbaneja, A. (2018). Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl*, 63(1), 39–59. https://doi.org/10.1007/s10526-017-9801-4

Vargas, R. I., Piñero, J. C., & Leblanc, L. (2015). An overview of pest species of *Bactrocera* fruit flies (Diptera: Tephritidae) and the integration of biopesticides with other biological approaches for their management with a focus on the Pacific region. *Insects*, 6(2), 297–318. https://doi.org/10.3390/insects6020297

Whitehorn, P. R., O'Connor, S., Wackers, F. L., & Goulson, D. (2012). Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science*, *336*(6079), 351–352. https://doi.org/10.1126/science.1215025

World Bank Group. (2022). *Pakistan country climate and development report*. World Bank. https://openknowledge.worldbank.org/handle/10986/38277

Wyckhuys, K. A. G., Van der Werf, W., Hughes, A. C., & Zalucki, M. P. (2013). Conservation biological control in Asia: A research agenda. *CAB Reviews*, *8*, 1–12. https://doi.org/10.1079/PAVSNNR20138048

Yellajosula, G., Cihacek, L., Faller, T., & Schauer, C. (2020). Soil carbon change due to land conversion to grassland in a semi-arid environment. *Soil Systems*, *4*(3), 43.

Yousaf, A. A., Sarfraz, K., Ahmed, A., Hassan, I., Ali, H., & Mehmood, T. (2023). Storage stability assessment of indigenous guava fruits (Psidium guajava L.) cv. "Gola" in response to γ-irradiation. *Journal of Food Processing and Preservation*, 2023, Article ID 4546469. https://doi.org/10.1155/2023/4546469

Zahoor, S., Anwar, F., Qadir, R., Soufan, W., & Sakran, M. (2023). Physicochemical attributes and antioxidant potential of kernel oils from selected mango varieties. *ACS Omega*, *8*(25), 22613–22622. https://doi.org/10.1021/acsomega.3c01155

IEER
Institute for Excellence in Education & Research