



Integrated pest and pollinator management in India: A way forward to sustainable agriculture

YOUSRA MUKHTAR^{1*} and UMA SHANKAR¹

*Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu,
Jammu and Kashmir 180 009, India*

Received: 17 March 2023; Accepted: 03 August 2023

ABSTRACT

Pollinators play a vital role in sustaining both cultivated and wild plants, thus ensuring the well-being of humanity. Unfortunately, the indiscriminate methods employed in pest-management have a detrimental impact on beneficial fauna, especially pollinators. Taking into account the harmful effects of pesticides on pollinators and the lack of explicit consideration for their welfare in Integrated Pest Management (IPM) practices, there is an urgent need to integrate pollinator management into the IPM programme. Incorporating pollinator management within the IPM framework is essential for maintaining the health of pollinators, preserving diverse pollinator species and achieving optimal crop yields with reduced pest-related issues- aspects that are often overlooked in conventional pest management approaches. This transformation from IPM to IPPM (Integrated Pest and Pollinator Management) highlights the importance of selectively and judiciously employing pesticides and other pest control strategies that have minimal impact on the habits, habitats, reproductive capabilities, foraging behaviour, growth, development and survival of pollinators. Although the concept of IPPM was introduced by Biddinger and Rajote (2015), our focus lies in explaining its relevance within the Indian context. Here, IPPM is imperative for reducing pest populations below economically damaging thresholds while simultaneously enhancing and conserving pollinators. By achieving this delicate balance, the ecological equilibrium can be preserved, ensuring the continued existence of various species and sustainability of our ecosystem.

Keywords: Conservation, Ecological balance, Pesticides, Pollinators

Pollinators are the agents that carry pollen from male to female flowers of the same or different plant for pollination (Sukumaran *et al.* 2020). Pollination is an important prerequisite for the process of fertilization (Lord and Russell 2002) and the development of seed or fruit in agricultural or horticultural crops (Shakya and Bhatla 2018). Over 2,00,000 species of pollinators are animals, wherein around 75% of crop plants pollination is contributed by insects (Aizen *et al.* 2009). Coleoptera (beetles), Diptera (true flies), Lepidoptera (butterflies and moths) and Hymenoptera (bees, wasps, and ants) are important insect orders that pollinate thousands of crop species worldwide (Ollerton *et al.* 2011). Honeybees and wild bees are vital for pollination of fruits, vegetables and other crops, and their conservation is equally important (Abrol *et al.* 2012). There would be almost a 3–8% global decline in agricultural production in the absence of pollinators (Aizen *et al.* 2009). Pollinators

not only aid in pollination but also improvise the yield and quality of the crops, thus increasing marketability and securing the food demand, subsequently (Bartomeus *et al.* 2014). In addition to monetary benefits, pollinators also have an important role to play in aesthetic, religious, cultural and recreational activities (Chagnon *et al.* 2015). However, a shift from traditional to modern agriculture has had a drastic effect on the population dynamics and survival of pollinators (Ayres and Schneider 2009). The indiscriminate and non-judicious pesticides use and more reliance of farmers on chemical control of insect and non-insect pests has not only led to environmental degradation and ecological imbalance but also a gradual decline in pollinator population (Whitehorn *et al.* 2012). Moreover, farmers tend to manage insect pests, pathogens and weeds while neglecting the impact of pest management activities on pollinators. As such, there is a pressing need to integrate pest and pollinator management on a single scale for efficient pest management while simultaneously keeping the population of pollinators in harmony (Biddinger and Rajote 2015). The fact that IPM (Integrated Pest Management) is pest-centered inevitably requires additional details in its design when dealing with other trophic groups. In an attempt to optimize

¹Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu, Jammu and Kashmir.

*Corresponding author email: syedyusra4@gmail.com

the simultaneous management of pests and beneficial pollinators, the concept of IPPM (Integrated Pest and Pollinator Management) was introduced by Biddinger and Rajote (2015). The present article endeavours to elucidate the notion within the Indian context and potential requisite actions that could favour pollinators while deterring pests exclusively.

Pesticide-pollinator conflict

India, being a tropical country, exhibits a highly asymmetrical utilization pattern of insecticides (Bhardwaj and Sharma 2013). The insecticide application in India differs significantly from global practices wherein people utilize approximately 44% insecticides. Contrarily, Indian farmers account for a substantial 76% of total insecticide usage (Mathur and Tannan 1999). This substantial disparity in insecticide consumption underscores unique agricultural and pest management challenges faced by Indian farming community. These pesticides induce negative effects on pollinators which is very evident (Bhardwaj and Sharma 2013). The increased and non-judicious pesticides use not only makes the pests resistant but also harms pollinators (Baskar *et al.* 2017). Several instances of 'bee-kill' due to insecticide exposure have been reported in India (Stanley *et al.* 2015, Sowmiya and Sankarganesh 2019). Many scientists reported a catalogue of complexities in pesticide-pollinator interaction which involved combinatorial exposures (Mullin *et al.* 2010), sublethal effects (Desneux *et al.* 2007), synergism and interactions (Sanchez-Bayo *et al.* 2016), buffering mechanism in social colonies (Henry *et al.* 2017), intraspecific and interspecific variation in susceptibility (Poquet *et al.* 2016), and unexpected routes of exposure (Krupke *et al.* 2012). Direct pesticide exposure to foraging bees or indirect exposure through carryover effects from past exposure reduced reproduction and population growth in bees by 20% (Stuligross and Williams 2021). The direct exposure of bees and other pollinators to various insecticides has had lethal effects on them (Blacquiere *et al.* 2012) and the pollinator population has declined in enormous numbers (Sponsler *et al.* 2019). Not only due to direct exposure, but indirect exposure through pesticide residues have sublethal effects on bee communities leading to their ramification (Pamminger *et al.* 2018). For instance, when Novaluron (Chitin Synthesis Inhibitor) is applied to alfalfa crop during flowering, it does not produce direct toxicity on adult bees, rather imposes sublethal effects on honeybee reproduction (Hodgson *et al.* 2011). The continuous exposure of pollinators to insecticides and fungicides or their residues drastically alters the foraging ability, pollination potential, size, structure, life cycle, and feeding behaviour of pollinators (Tennekes and Sanchez-Bayo 2012). The novel group of insecticides have rapidly and efficiently managed insect pests below their threshold levels (Deep *et al.* 2018) but have simultaneously caused sublethal effects in pollinators (Desneux *et al.* 2007), especially bees when used irrationally and outside their recommended dosage. In 1990s, neonicotinoids, a newer

class of insecticides, was commercially introduced to pest management system to reduce negative impact of earlier introduced insecticides (organochlorines, organophosphates, carbamates) on vertebrates (Lundin *et al.* 2015). Although vertebrate-safe with reduced pest resistance, neonicotinoids substantially contributed to decline of some bee species by adversely affecting their health (Blacquiere *et al.* 2012). Neonicotinoids have been found in pollen loads foraged by honey bees (Chauzat *et al.* 2006) and in stored pollen within bee hives (Krupke *et al.* 2012). Previous works have correlated neonicotinoid application with Colony Collapse Disorder (CCD) in bees (Medrzycki *et al.* 2010) in which the worker bees leave their hives despite all the available resources leaving queen bee behind, thus drastically declining bee colonies (Henry *et al.* 2012). However, no direct link between CCD and insecticides has been found yet, though many insecticide residues have been found in the beehives (Mullin *et al.* 2010). However, bee's exposure to insecticides interacts with other factors like parasites or virus which weakens the colony health and enhances bee's susceptibility to CCD. The combined effect of honeybee gut parasites (*Nosema ceranae* and *Nosema apis*) and sub-lethal doses of neonicotinoids have been reported by many studies (Sanchez-Bayo *et al.* 2016). The bee mortality increases more due to combined exposure to imidacloprid, *N. ceranae*, and *N. apis* as compared to exposure to neonicotinoids or *Nosema* infections alone (Alaux *et al.* 2010). The death of bees is not the sole outcome of pesticides, but these chemicals affect honey bees' foraging ability, communication, and other cognitive abilities (Desneux *et al.* 2007). Incerti *et al.* (2003) conducted a study in which bumble bees were exposed to blooming cucumbers within a flight cage treated with imidacloprid (field dose) and found that one-third of the population of bumble bees died within 48 h of exposure. As such, efficient and strategic management of pest populations is required to reduce pesticide resistance through reduced insecticidal applications (Sowmiya and Sankarganesh 2019), which would not only maintain pests below threshold levels but also strengthen the pollinator population (Ara and Haque 2021).

Six decades of integrated pest management

With continuous surge in insecticide application and negative impact of chemicals on beneficial organisms, there arose a need to tackle these problems through more reliance of farmers on non-chemical means of pest management (Abrol and Shankar 2012a). During golden age of insecticides (late 1940s and early 1950s) (Casida and Quistad 1998), farmers would indiscriminately spray insecticides even if the pest population was below threshold level (Coats 2012). This not only eradicated some important insects from crop ecosystem (Sánchez-Bayo 2012) but also marked a negative impact on population of natural enemies and pollinators (Desneux *et al.* 2007), thus imprinting an imbalance in natural ecosystem. The increased cases of pesticide resistance and ecological disasters put peer pressure on scientists to think of novel way for pest control. To

stabilize the ecosystem, the concept of Pest Management was introduced by Geier and Clark (1961). Further on, due to addition of more means of managing pests, R. F. Smith and R. Van den Bosch introduced the term Integrated Pest Management in 1967 (Smith and Van den Bosch 1967). In 1973, IOBC (International Organization for Biological and integrated Control of noxious animals and plants) defined Integrated Pest Management as “a pest control system that uses a set of methods that satisfy economic, ecological and toxicological requirements by giving priority to natural control and by respecting tolerance thresholds”. Integrated pest management (IPM) involves careful and proper use and integration of different pest control measures that reduce the pest population build-up with minimum and justified reliance on chemical measures to minimize risks to non-target organisms (Ehi-Eromosele *et al.* 2013). In IPM, different approaches to tackle pest problems, viz. cultural, mechanical, physical, chemical, legislative, and genetic control measures are integrated on a single scale to bring pest population below economic threshold level while simultaneously maintaining ecological balance (Ehi-Eromosele *et al.* 2013). IPM does not aim at completely eradicating the pest population from crop ecosystem, rather it aims at maintaining pest population below that causing economic injuries for sustenance and efficient functioning of ecosystem (Smith and Van den Bosch 1967). However, pollinators are not always adequately conserved in IPM practices because IPM primarily focuses on pest control and managing crop damage (Egan *et al.* 2020). While IPM aims to minimize use of pesticides and adopt more environment friendly approaches, its primary goal is to protect crops from pests and maximize yields (Abrol and Shankar 2012a). Lack of emphasis, knowledge gaps, economic priorities, and trade-offs are some reasons why pollinators do not receive sufficient attention in IPM. To address these issues, it is essential to raise awareness about the crucial role of pollinators in agriculture and ecosystem health. Efforts should be made to integrate pollinator-friendly practices into IPM strategies, promoting the use of alternative pest control methods that do not harm pollinators. Sustainable and holistic approaches that consider both pest management and pollinator conservation can help strike a balance between agricultural productivity and environmental protection.

Integrated pest and pollinator management

It is not a hidden fact that honey bees are the major pollinators of fruits and other crops (Calderone 2012). Not only *Apis* bees, but non-*Apis* bees like bumble bees, solitary bees, and syrphid flies have substantial contributions to pollination services, thus improvising crop yield (Abrol *et al.* 2012). Recent years have witnessed an upsurge in foraging by significant population of non-*Apis* pollinators on economically important crops like *Paulownia fortunei* (Shankar and Abrol 2015), *Parkinsonia aculeate* (Shankar *et al.* 2017a), *Ocimum basilicum* (Abrol *et al.* 2017), *Grewia asiatica* (Abrol and Shankar 2021), *Pongamia pinnata* (Shankar *et al.* 2017), vegetable crops like cucumber

and bitter melon (Dorjay *et al.* 2017), pulses (Abrol and Shankar 2015) like *Cajanus cajan* (Singh *et al.* 2017) and oilseeds (Abrol and Shankar 2012b) like *Sesamum indicum* (Shankar and Mukhtar 2022) and *Helianthus annuus* (Shankar and Mukhtar 2023). However, farmers in India take meager interest in the sustainability and augmentation of these *Apis* and non-*Apis* pollinators as their major context of concern is reduced pests and enhanced yield. Some farmers are not even aware of the importance of pollinators and neglect this concern during pest management programmes. Many farmers in southern India randomly introduce bee colonies in their plantation crop fields without having complete knowledge of the compatible bee species, which leads to inadequate pollination, competition and displacement of native pollinators, pest and disease infestations and negative environmental impact (Tej *et al.* 2017). Additionally, chemical control, an important aspect of IPM, has several positive aspects like rapid knockdown effect, easy accessibility, and comparatively low cost, when used appropriately. However, irreversible social, economic, and environmental impacts can be laid by chemical control when used without technical knowledge (Castro 2009). Pollinator health is damaged by many approved pesticides at doses used in agriculture which is attributed to systemic failure in the regulation of pesticides (Baskar *et al.* 2017). In addition, habitat loss, nesting site disruption, climate change, pollution, and reduced plant quality contribute substantial threats to pollinator decline in India (Basu *et al.* 2011). Such are the reasons that the pollinator population has considerably declined over the past years (Potts *et al.* 2010) because the safety and survival parameters of the most important insect species-the pollinators has been lost somewhere in our everyday pest control programmes (FAO 2016). It is, thus, needed that these pollinators are managed on an integrated scale to sustain their population and increase their efficiency to sustain our livelihood. The concept of Integrated Pollinator Management resembles Integrated Pest Management (IPM) in using diverse control measures simultaneously (Lundin *et al.* 2021), however, the difference lies in the fact that in Integrated Pollinator Management, enough emphasis is given to using various management practices to protect pollinators and sustain their population along with improvisation of their foraging abilities, fecundity, and rate of pollination. Thus, the two concepts have been merged as Integrated Pest and Pollinator Management (IPPM) to co-manage pests and pollinators on same scale (Biddinger and Rajotte 2015). The concept of IPPM was initially restricted specifically to practices that reduce pollinators exposure to conventional pesticides (Biddinger and Rajotte 2015). However, there is a need to incorporate other management tactics of IPM as well. In IPPM, proactive landscape and crop field management are crucial in which reactive human-based inputs such as pesticides can be incorporated (Egan *et al.* 2020).

Need to shift from IPM to IPPM

Insects are an integral part of the natural ecosystem

for the maintenance of its proper balance (Scudder 2017). However, due to certain anthropogenic activities and sometimes, due to natural reasons, insects develop the status of a pest (Prakash and Verma 2022). Thus, pest problems go hand in hand with crop production and farmer needs to manage these pest problems from time to time for sustainable crop production. However, regardless of the need, a farmer adopts various agronomic, chemical, or other pest prevention measures which not only alter the pests' microclimate but also negatively affect the pollinators' inhabiting structures and their feeding sites. Many measures of IPM taken to significantly reduce the pest population have positive effects on pollinators (Johansen and Mayer 1990), however, some measures can have neutral or negative impacts as well (Glenny *et al.* 2022). For example, hedgerows or flower borders which are grown in fields as a source of food and shelter for natural enemies, also supply pollen and nectar to pollinators and thus, provide a pathway for pollination services (Blaauw and Isaacs 2014). However, increasing use of mechanical measures of pest control (say, the use of nets to exclude insect pests) can hurt pollinating insects (Manja and Aoun 2019). The phylogeny and ecology of insect pests, their predators, and crop pollinators overlap and this creates a potential for their co-management, thus emphasizing the need for IPPM (Lundin *et al.* 2021). The co-management is also important because the same insect species can act as crop herbivores, predators, or pollinators. For example, larval hoverflies are predators but their adults are pollinators and few bee species (*Trigona spinipes*) can act as pollinators or pests based on the crop type (Saunders *et al.* 2016). The reduced use of pesticides positively influences the survival and efficiency of predators in reducing the pest population. The need-based and systematic use of pesticides and more reliance on natural and eco-friendly management of insect pests will have a positive impact on the reduction of pest species accompanied by the augmentation of pollinators, thus increasing crop pollination and productivity. IPPM, thus, consists of those strategies and tactics that share benefits between pollination and pest control and provide complementary or synergistic benefits for yield, and at the same time mitigate potential conflicts (e.g. ecosystem disservices) (Egan *et al.* 2020). IPPM acts as a framework that can be implemented to co-manage pests, natural enemies and pollinators for proper ecosystem functions (Lundin *et al.* 2021).

Karuppaiah and Soumia (2020) reported quality seed production of the onion by Integrating Pest and Pollinator Management (IPPM) strategies and opined several management practices for the conservation of chief pollinators of onion (honey bees) and sustainable onion production, viz. seed bulb dipping, safer application of insecticides as window strategy (no pesticide spraying after the opening of flowers), habitat manipulation by making neighbouring crops of onion displeasing to bees to enhance their quality visits and foraging on onion, balanced use of fertilizers, good irrigation practices and managed pollination by the systemic placing of bee hives within the field for

improving the amount, time and type of visitation by the bees.

6 P's concept of IPPM

Integrated Pest and Pollinator Management (IPPM) has now become imperative in the contemporary era, advocating for the conservation of pollinators and the sustenance of human populations (Biddinger and Rajotte 2015). Undeniably, pollinators play a pivotal role in maintaining species viability and ecological equilibrium (Ollerton 2021). Nevertheless, as previously discussed, pesticides disrupt pollinators' foraging patterns and survival, along with impacting other natural enemies. Hence, we introduce the concept of the 6 P's in IPPM, which necessitates careful consideration before embarking on any pest control programme. These 6 P's encompass Plant, Pest, Pesticide, Predator, Parasitoid, and Pollinator. The interrelation among these factors is intricate: pests exploit specific host plants where their predators and parasitoids might also reside, and pollinators actively participate in plant fertilization (Calatayud *et al.* 2018). Pests inflict detrimental effects on plants, while predators and parasitoids contribute to pest regulation and serve as valuable assets (Ballal and Verghese 2015). Pollinators, in turn, confer direct benefits upon plants and human well-being (Ollerton 2021). Indiscriminate pesticide application curtails pest populations but engenders deleterious consequences for predators, parasitoids and pollinators (Table 1, Fig 1). Pesticide application exerts both positive and negative impacts on plants, contingent on the dosage, timing, and application method. Pesticides offer benefits to plants by reducing pest populations and mitigating plant damage, but their excessive and indiscriminate use can lead to heightened phytotoxicity. Non-judicious pesticide application elevates selection pressure on pest populations, resulting in the emergence of pesticide resistance, pest resurgence, and secondary pest outbreaks. Moreover, important beneficial organisms, such as predators, parasitoids and pollinators, also experience adverse effects due to extensive pesticide application. Hence, IPPM suggests pest control on a plant in such a way that it should reduce the population of pests without altering the behaviour and survival of predators, parasitoids, or pollinators (Egan *et al.* 2020). Pests, when present in lower numbers, do not cause any economic damage to the grower, a non-chemical measures of pest prevention and management are advised to be taken (Held 2020). It's only after pests go beyond economic threshold level than control measures should be adopted, and only under uncontrollable situations, pesticide application should be followed (Kaur and Kaur 2020). However, pesticides selected for pest control should be such that they do not cause any harm to non-target organisms, especially pollinators. Also, the pesticides applied should not cause negative effects on plants like oxidative stress or any toxicity which would later affect their growth and development (Parween *et al.* 2016). Henceforth, farmers are encouraged to consider the application of selective, eco-friendly or biorational pesticides that specifically target

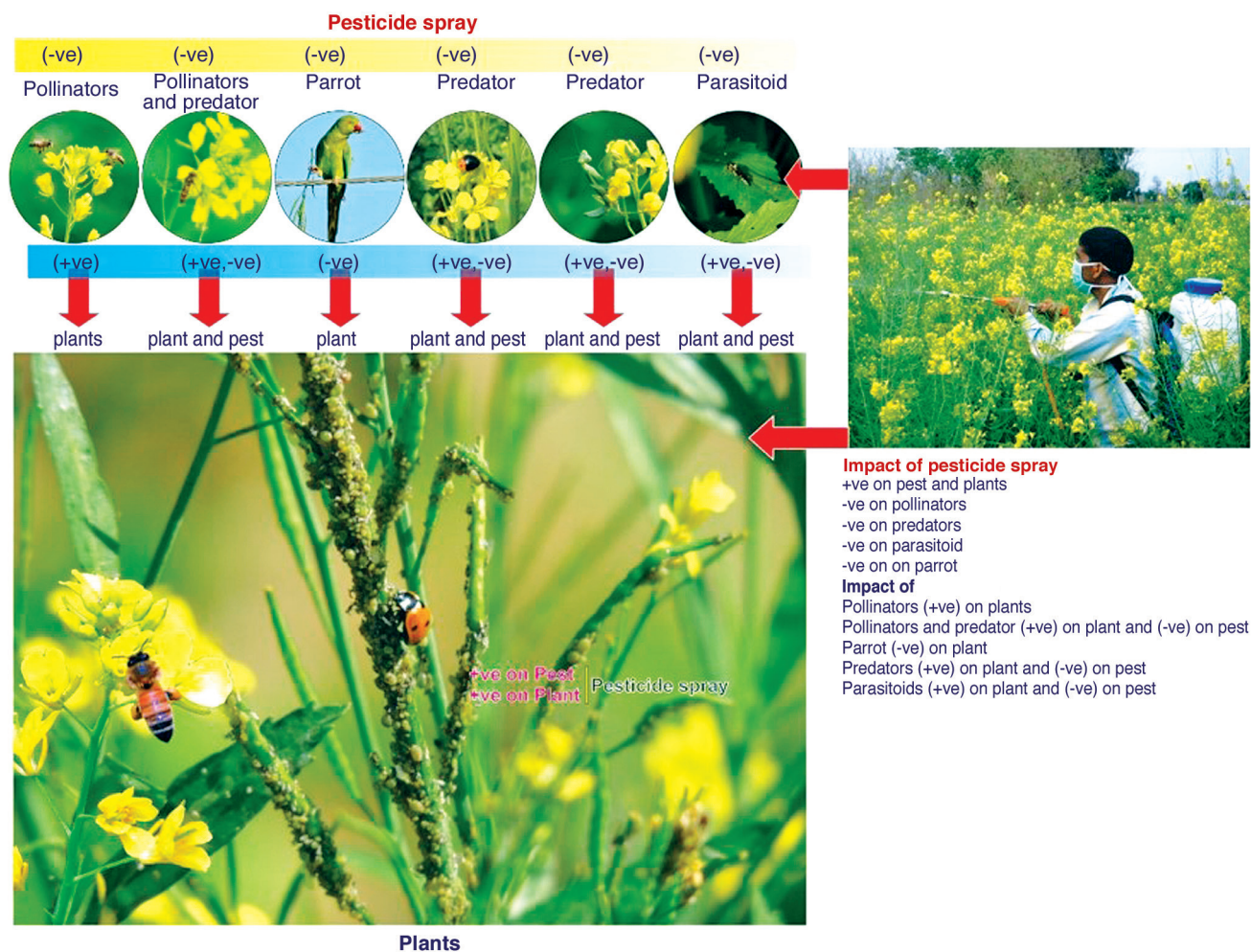


Fig 1 Impact of biotic organisms on each other and effect of pesticide spray on them.

pests while sparing other beneficial organisms thriving on the plant (Tijjani *et al.* 2016).

National and international framework and policies

An International Pollinators Initiative was established by Conference of Parties (COP) to Convention on Biological Diversity in May 2000 for sustainable use and conservation of pollinators and was adopted in April 2002. This initiative's main focus was to monitor pollinators' population decline for probable reasons, determine economic loss due to pollinator decline, and conserve and restore the diversity of pollinators in agriculture and allied fields. The development and implementation of various pollinator initiatives have been catalyzed by International Pollinators Initiatives such as Oceania Pollinator Initiative, North American Pollinator Protection Campaign, Brazilian Pollinators Initiative, Pollinator Partnership Action Plan (USA), Canadian Pollination Initiative, African Pollinator Initiative, All-Ireland Pollinator Plan, European Pollinator Initiative, National Pollinator Strategy for bees and other pollinators in England, Dutch Pollinator Strategy and Swiss National Action Plan for Bee Health (Eardley 2001). The assessment report on Pollinators, Pollination and Food

Table 1 Impact of pesticides on plants and associated insect fauna

	Pesticides impact	
	Positive impact (+)	Negative impact (-)
Plant	+*	-
Pest	+	-**
Predator		-
Parasite		-
Pollinator		-

*Pesticides positively affect plant through reduction of phytophagous pests and improvement and rejuvenation of plant wear and tear; **pesticides show negative impact on pests in the form of resistance build-up, pest resurgence, or secondary pest outbreak.

Production by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IBPES) has provided available information on pollinators as being regulators of ecosystem. This assessment is concerned with monetary and non-monetary role of wild and domesticated pollinators, their role in pollination, and factors responsible for their changing status along with their impact on human beings.

The 13th meeting of COP at UN Biodiversity Conference held in Mexico, in 2016 recognized the assessment report of IBPES and realized the contribution of pollinators to Sustainable Development Goals. It also emphasized fostering policy measures and innovative actions to protect pollinators. This decision encourages government and non-government organizations to take necessary measures in this regard and make equivalent efforts in conserving and augmenting pollinators' population and collectively reduce factors responsible for their decline.

During 2000–17, 36 USA states passed 110 policies about pollinators, viz. i) improved apiculture standards to manage their diseases and pests; ii) task forces to update pest management approaches; iii) pollinator habitat establishment and improvement; iv) funded monitoring and research on native insect pollinators, and v) increased public involvement and awareness on pollinators. In 1995, The Forgotten Pollinators Campaign was launched in North America followed by book publication under same name (Buchmann and Nabhan 1996), and this campaign demanded changes in policy that would favour pollinators habitat (Ingram *et al.* 1996). The United States implemented two policies in favour of insect pollinators, viz. designing a state insect and pollinator week in 2006, and by 2016, all of the United States had designated and implemented pollinators weeks under the preambles “pollinator species such as birds and insects are essential partners of farmers and ranchers in producing much of our food supply”, “pollination plays a vital role in the health of our national forests and economic development” and “pollinator species provide significant environmental benefits that are necessary for maintaining healthy, biodiverse ecosystems”. In this accordance, New Mexico also designated the Sandia hairstreak butterfly (*Callophrys mcfarlandi*) as state butterfly to bring its aesthetic values to notice (Hall and Steiner 2019).

The Government of India has taken an initiative to include pollinators as a principle component of IPM with more focus directed at advocating such pest management strategies that would favour the pollinators and sustain their populations. It has taken necessary steps to reduce overuse and ensure proper use and disposal of pesticides by agriculture and horticulture growers in India. In this regard, the GoI established ICAR-NCIPM (National Centre for Integrated Pest Management) in 1988 to reduce pest-induced yield losses and maximize crop productivity. Since then, it has validated and refined several strategies in favour of IPM like conservation of beneficial organisms, adequate training and knowledge for farmers, beforehand pest prevention measures, use of Information and Communication Technology (ICT), and so on. It also promotes the need-based use of synthetic pesticides at their recommended doses along with careful follow-up of their label instructions. The data collected regarding pesticide residues under “Monitoring of Pesticide Residues at National Level” is dealt by concerned officials to impose proper implications of pesticide use by context of IPM approach and create awareness among growers and pesticide dealers (Dar *et al.* 2020). However,

necessary policies in this regard need to be developed or implemented in India that reduce impact of chemicals on beneficial insects and provide alternative, pollinator-friendly approaches to pest management.

Benefits of IPPM

- Increased focus on sustainable crop pollination and pest control.
- Target pest control with broader environmental benefits and sustainable ecology.
- Reduced trade-offs along with increased co-benefits of pest and pollinator management.
- Reduced exposure of pollinators to harmful pesticides, thus making the environment ‘pollinator friendly’.
- Enhanced crop productivity by selected pest reduction and pollinator enhancement.

Way forward

Insect pests are indispensable part of every ecosystem and we must manage only those pests whose population is above economic threshold level (El Bouhssini and Trissi 2018). Further, chemical and conventional methods of pest control should be avoided, and try to prefer non-chemical and organic measures of pest management. In case of pest outbreak or likewise situation where chemical pest management is direly needed, adopt the following measures:

- i. Carefully read the label on chemical to check for its safe handling and use along with hazardous impact on pollinators.
- ii. Do not apply pesticides near nesting or foraging sites of pollinators.
- iii. Avoid pesticide application at the time of peak pollinator activity.
- iv. Use pesticides that have coarse droplet sizes to avoid their drift into pollinators' habitats.
- v. Before pesticide spraying, check for wind speed and direction to avoid drift.
- vi. Try to use less persistent pesticides or the ones that are easily degradable to avoid their biomagnification within the pollinator ecosystem.
- vii. Ensure more reliance on biopesticides or selective pesticides that do not harm non-target organisms.
- viii. Avoid agronomic practices that involve physical manipulation of pollinators' habitat.
- ix. Conserve natural biodiversity by planting more flower resources within agricultural ecosystem to ensure proper foraging and feeding sites for pollinators (Jackson *et al.* 2007).
- x. Plant hedges of grass or shrubs between area of pesticide application and pollinator nests to avoid drift to their environment.
- xi. Encourage cultivation of such crops that are pest resistant but simultaneously encourage foraging by pollinators (Sponsler *et al.* 2019).

Conclusion

Pollinator management is of equal importance as

pest management and should be greatly pondered over due to neglected impact of pest control tactics besides other anthropogenic activities on pollinators' survival and foraging capabilities. Thus, Integrated Pest and Pollinator Management (IPPM) provide a pathway for co-management of pollinators in parallel to the pest. IPPM encourages farmers for careful and strategic use of pesticides in a way that is least effective on pollinators and their habitat. The initiation and implementation of state, national, policies and awareness programmes in favour of pollinators' population enhancement by state and central government should be emphasized. In addition to this, local people should come upfront in developing pollinator management as a daily hobby and take keen interest in mending ways by which factors for pollinator decline can be reduced at our local level. Proper vigilance, monitoring and complete knowledge, and understanding are, thus, required before implementing any pest management programme to check its negative impact on pollinators for effective conservation of pollinators, ecosystem's sustenance and enhancement of crop production and productivity.

REFERENCES

- Abrol D P and Shankar U. 2012a. *Integrated Pest Management: Principles and Practice*. CAB International, Wallingford.
- Abrol D P and Shankar U. 2012b. Pollination in oil crops: Recent advances and future strategies. *Technological Innovations in Major World Oil Crops*, pp. 221–67. Gupta S K (Ed). Springer Science + Business Media, LLC.
- Abrol D P and Shankar U. 2015. Role of pollination in pulses. *Advances in Pollen Spore Research*, pp. 101–03. Raju A J S (Ed). Today and Tomorrow's Printers and Publishers, New Delhi.
- Abrol D P and Shankar U. 2021. Phalsa is an excellent forage plant for bees and other visiting insects. *Bee World* **98**(3): 100–03.
- Abrol D P, Shankar U and Chatterjee D. 2017. Foraging rhythm of bees in relation to flowering of sweet basil (*Ocimum basilicum* L). *Current Science* **113**(12): 2359–62.
- Abrol D P, Shankar U, Chatterjee D and Ramamurthy V V. 2012. Exploratory studies on the diversity of bees with special emphasis on non-*Apis* pollinators in some natural and agricultural plants of Jammu division. *Current Science* **103**: 780–83.
- 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. *Annual Botany* **103**: 1579–88.
- Alaux C, Brunet J L, Dussaubat C, Mondet F, Tchamitchan S, Cousin M, Brillard J, Baldy A, Belzunces L P and Le Conte Y. 2010. Interactions between *Nosema* microspores and a neonicotinoid weaken honeybees (*Apis mellifera*). *Environmental Microbiology* **12**: 774–82.
- Ara Z and Haque A R. 2021. A comprehensive review on synthetic insecticides: Toxicity to pollinators, associated risk to food security, and management approaches. *Journal of Biosystems Engineering* **46**: 254–72.
- Ayres J S and Schneider D S. 2009. The role of anorexia in resistance and tolerance to infections in *Drosophila*. *PLoS Biology* **7**: 1000–05.
- Ballal C R and Verghese A. 2015. Role of parasitoids and predators in pest management. *New Horizons in Insect Science: Towards Sustainable Pest Management*, pp. 307–26. Chakravarthy A K (Ed.). Springer, India.
- Bartomeus I, Potts S G, Steffan-Dewenter I, Vaissière B E, Woyciechowski M, Krewenka K M, Tscheulin T, Roberts S P, Szentgyorgyi H, Westphal C and Bommarco R. 2014. Contribution of insect pollinators to crop yield and quality varies with agricultural intensification. *Peer J* **2**: e328.
- Baskar K, Sudha V and Jayakumar M. 2017. Effect of pesticides on pollinators. *Ecology and Environmental Science* **2**(8): 00052.
- Basu P, Bhattacharya R and Iannetta PPM. 2011. A decline in pollinator-dependent vegetable crop productivity in India indicates pollination limitation and consequent agro-economic crises. *Nature Precedings*: hdl:10101/npre.2011.6044.1
- Bhardwaj T and Sharma J P. 2013. Impact of pesticides application in agricultural industry: An Indian scenario. *International Journal of Agriculture and Food Science Technology* **4**(8): 817–22.
- Biddinger D and Rajotte E G. 2015. Integrated pest and pollinator management-adding a new dimension to an accepted paradigm. *Current Opinion in Insect Science* **10**: 204–09.
- Blaauw B R and Isaacs R. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *Journal of Applied Ecology* **51**: 890–98.
- Blacquiere T, Smagghe G, Cornelis A M, Gestel van and Mommaerts V. 2012. Neonicotinoids in bees: A review on concentrations, side-effects and risk assessment. *Ecotoxicology* **21**: 973–92.
- Buchman S L and Nabhan G P. 1996. *The Forgotten Pollinators*. Island Press, Washington, DC.
- Calatayud P-A, Sauvion N and Thiery D. 2018. *Plant-Insect Interactions*. Oxford Bibliographies.
- Calderone N W. 2012. Insect pollinated crops, insect pollinators, and US agriculture: Trend analysis of aggregate data for the period 1992–2009. *PLoS ONE* **7**: e37235.
- Casida J E and Quistad G B. 1998. Golden age of insecticide research: past, present, or future? *Annual Review of Entomology* **43**(1): 1–16.
- Castro V L S S. 2009. Use of pesticide mixtures in agriculture and their toxicological implications on health. *Journal of the Brazilian Society of Ecotoxicology* **4**(1–3): 87–94.
- Chagnon M, Kreutwizer D, Mitchell E A D, Morrissey C A, Noome D A and Sluijs J P. 2015. Risks of large-scale use of systemic insecticides to ecosystem functioning and services. *Environmental Science and Pollution Research International* **22**(1): 119–34.
- Chauzat M P, Faucon J P, Martel A C, Lache J, Cougoule N and Aubert M. 2006. A survey on pesticide residues in pollen loads collected by honey bees (*Apis mellifera*) in France. *Journal of Economic Entomology* **99**: 253–62.
- Coats J R. 2012. *Insecticide Mode of Action*. Academic Press.
- Dar S A, Farook U, Javeed K, Mir S H, Yaqoob M, Showkat A, Kundoo A A, Hassan R and Islam T. 2020. Pesticide legislation, and national and international policies to maintain sustainable crop production through insect pollinator intervention. *International Journal of Chemical Studies* **8**(6): 34–41.
- Deep G, Patil J, Yadav S, Kumer B and Nath R. 2018. Novel insecticides: A potential tool for the management of insect pest. *Journal of Entomology and Zoology Studies* **6**(5): 277–81.
- Desneux N, Decourtye A and Delpuech J M. 2007. The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology* **52**: 81–106.

- Dorjay N, Abrol D P and Shankar U. 2017. Insect visitors on cucumber and bitter melon flowers and impact on quantity of crop production by different pollination treatments. *Journal of Apiculture* **32**(2): 77–88.
- Eardley C D. 2001. *Pollinators: A Conservation Priority*. Science in Africa. <http://scienceinafrica.co.za/pollinators.htm>
- Egan P A, Dicks LV, Hokkanen H M and Stenberg J A. 2020. Delivering integrated pest and pollinator management (IPPM). *Trends in Plant Science* **25**: 577–89.
- Ehi-Eromosele O C, Nwinyi and Ajani O O. 2013. Integrated pest management. *Weed and Pest Control- Conventional and New Challenges*, pp. 105–15.
- El Bouhssini M and Trissi A N. 2018. Integrated pest management: Economic threshold and economic injury level. *Date Palm Pests and Diseases Integrated Management*, pp. 14–19. ICARDA publishing.
- FAO. 2016. Pollinators vital to our food supply under threat. Food and Agriculture Organization of the United Nations. *Cahiers Agricultures* **8**: 389–96.
- Geier P W and Clark L R. 1961. An ecological approach to pest control. (In) *Proceedings of 8th Technical Meetings International Union for the Conservation of Nature and Natural Resources*, pp. 10–18. Warsaw, Poland.
- Glenny W, Runyon J B and Burkle L A. 2022. A review of management actions on insect pollinators on public lands in the United States. *Biodiversity Conservation* **31**: 1995–2016.
- Hall D M and Steiner R. 2019. Insect pollinator conservation policy innovations at sub-national levels: Lessons for lawmakers. *Environmental Science Policy* **93**: 118–28.
- Held W D. 2020. Nonchemical approaches to pest management. *Urban Landscape Entomology*. Academic Press, Cambridge, Massachusetts.
- Henry M, Becher M A and Osborne J L. 2017. Predictive systems models can help elucidate bee declines driven by multiple combined stressors. *Apidologie* **48**: 328–39.
- Henry M, Beguin M, Requier F, Rollin O, Odoux J-F, Aupinel P, Aptel J, Tchamitch-ian S and Decourtye A. 2012. A common pesticide decreases foraging success and survival in honey bees. *Science* **336**: 348–50.
- Hodgson E W, Pitts-Singer T L and Barbour J D. 2011. Effects of the insect growth regulator, novaluron on immature alfalfa leafcutting bees *Megachile rotundata*. *Journal of Insect Science* **11**: 43.
- Incerti F, Bortolotti L, Porrini C, Micciarelli-Sbrenna A and Sbrenna G. 2003. An extended laboratory test to evaluate the effects of pesticides on bumblebees, preliminary results. *Bulletin of Insectology* **56**: 159–64.
- Ingram M, Nabhan G and Buchmann S. 1996. *Our Forgotten Pollinators: Protecting the Birds and Bees*. Global Pesticide Campaigner PANNA, San Francisco, CA.
- Jackson LE, Pascual U and Hodgkin T. 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. *Agriculture, Ecosystems and Environment* **121**(3): 196–210.
- Johansen C A and Mayer D F. 1990. *Pollinator Protection: A Bee and Pesticide Handbook*. Cheshire, Connecticut, Wicwas Press, USA.
- Karuppaiah V and Soumia P S. 2020. Integrated pests and pollinators management (IPPM) strategies for onion seed production. *Rashtriya Krishi* **15**(1): 87–89.
- Kaur T and Kaur M. 2020. Integrated pest management: A paradigm for modern age. *Pests, Weeds and Diseases in Agricultural Crop and Animal Husbandry Production*. Kontogiannatos D, Kourti A and Mended F (Eds.). Intech Open publishers, Rijeka.
- Krupke C, Hunt G J, Eitzer B D, Andino G and Given K. 2012. Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS One* **7**(1). doi:10.1371/journal.pone.0029268
- Lord E M and Russell S D. 2002. The mechanisms of pollination and fertilization in plants. *Annual Review of Cell and Development Biology* **18**: 81–105.
- Lundin O, Rundlof M, Jonsson M, Bommarco R and Williams N M. 2021. Integrated pest and pollinator management—expanding the concept. *Frontiers in Ecological Environment*. doi:10.1002/fee.2325
- Lundin O, Rundlof M, Smith H G, Fries I and Bommarco R. 2015. Neonicotinoid insecticides and their impacts on bees: A systematic review of research approaches and identification of knowledge gaps. *PLOS ONE* **10**(8): e0136928.
- Manja K and Aoun M. 2019. The use of nets for tree fruit crops and their impact on the production: A review. *Scientia Horticulturae* **246**: 110–22.
- Mathur S C and Tannan S K. 1999. Future of Indian pesticides industry in next millennium. *Pesticide Information* **24**(4): 9–23.
- Medrzycki P, Sgolastra F, Bortolotti L, Bogo G, Tosi S, Padovani E, Porrini C and Sabatini A G. 2010. Influence of brood rearing temperature on honey bee development and susceptibility to poisoning by pesticides. *Journal of Apicultural Research* **49**: 52–59.
- Mullin C A, Frazier M, Frazier J L, Ashcraft S, Simonds R, van Engelsdorp D and Pettis J S. 2010. High levels of miticides and agrochemicals in North American apiaries: Implications for honey bee health. *PLoS ONE* **5**: e9754.
- Ollerton J, Rachael W and Sam T. 2011. How many flowering plants are pollinated by animals? *Oikos* **120**: 321–26.
- Ollerton J. 2021. *Pollinators and Pollination: Nature and Society*. Pelagic Publishing Ltd, Exeter, UK.
- Pammingier T, Botias C, Goulson D and Hughes W O. 2018. A mechanistic framework to explain the immunosuppressive effects of neurotoxic pesticides on bees. *Functional Ecology* **32**(8): 1921–30.
- Parween T, Jan S, Mahmooduzzafar S, Fatma T and Siddiqui Z H. 2016. Selective effect of pesticides on plant-A review. *Critical Reviews in Food Science and Nutrition* **56**(1): 160–79.
- Potts S G, Biesmeijer J C, Kremen C, Neumann P, Schweiger O and Kunin W E. 2010. Global pollinator declines: trends, impacts and drivers. *Trends in Ecology and Evolution* **25**(6): 345–53.
- Poquet Y, Vidau C and Alaux C. 2016. Modulation of pesticide response in honeybees. *Apidologie* **47**: 412–26.
- Prakash S and Verma A K. 2022. Anthropogenic activities and biodiversity threats. *International Journal of Biological Innovations* **4**(1): 94–103.
- Sanchez-Bayo F. 2012. Ecological impacts of insecticides. *Insecticides—Advances in Integrated Pest Management*, pp. 61–90.
- Sanchez-Bayo F, Goulson D, Pennacchio F, Nazzi F, Goka K and Desneux N. 2016. Are bee diseases linked to pesticides?—A brief review. *Environment International* **89**(90): 7–11.
- Saunders M E, Peisley R K, Rader R and Luck G W. 2016. Pollinators, pests, and predators: recognizing ecological trade-offs in agroecosystems. *Ambio* **45**: 4–14.
- Scudder G G E. 2017. The Importance of Insects. *Insect Biodiversity*, pp. 9–43. Foottit R G and Adler P G (Eds.). Wiley Publishing.

- Shakya R and Bhatla S C. 2018. Pollination, fertilization and seed development. *Plant Physiology, Development and Metabolism*. Springer, Singapore.
- Shankar U and Abrol D P. 2015. Plants for bees: *Paulownia fortunei*. *Bee World* **92**(3): 57–93.
- Shankar U and Mukhtar Y. 2022. Diversity and foraging behaviour of pollinators on *Sesamum indicum* L. *Indian Journal of Ecology* **49**(5): 1984–88.
- Shankar U and Mukhtar Y. 2023. Pest management practices impact *Helicoverpa armigera* infestation and foraging behaviour of pollinators in sunflower. *International Journal of Pest Management*. <https://doi.org/10.1080/09670874.2023.2216667>
- Shankar U, Abrol D P, Chatterjee D and Rizvi S E H. 2017a. Diversity of native bees in *Parkinsonia aculeata* L. in Jammu region of North-West Himalaya. *Tropical Ecology* **58**(1): 211–15.
- Shankar U, Abrol D P and Singh A K. 2017b. Plants for bees *Pongamia pinnata* (L.) Pierre. *Journal of palynology* **53**: 133–37.
- Singh I, Shankar U, Abrol D P and Mondal A. 2017. Diversity of insect pollinators associated with pigeon pea, *Cajanus cajan* L. Mill sp. and their impact on crop production. *International Journal of Current Microbiology and Applied Science* **6**(9): 528–35.
- Smith R F and Van den Bosch R. 1967. Integrated control. *Pest Control: Biological, Physical and Selected Chemical Methods*, pp. 295–340. Kilgore W W and Doutt R L (Eds.). Academic Press, New York.
- Sowmya C and Sankarganesh E. 2019. Pesticide resistance and its management in insect pests. *Agrobios Newsletter* **18**(6): 82–83.
- Sponsler D B, Grozinger C M, Hitaj C, Rundlof M, Botías C, Code A and Douglas M R. 2019. Pesticides and pollinators: a socioecological synthesis. *Science of the Total Environment* **662**: 1012–27.
- Stanley J, Sah K, Jain S K, Bhatt J C and Sushil S N. 2015. Evaluation of pesticide toxicity at their field recommended doses to honey bees, *Apis cerana* and *A. mellifera* through laboratory, semi-field and field studies. *Chemosphere* **119**: 668–74.
- Stuligross C and Williams N M. 2021. Past insecticide exposure reduces bee reproduction and population growth rate. *PNAS* **118**(48): e2109909118.
- Sukumaran A, Khanduri V P and Sharma C M. 2020. Pollinator-mediated self-pollination and reproductive assurance in an isolated tree of *Magnolia grandiflora* L. *Ecological Processes* **9**: 45–53.
- Tej M K, Aruna R, Mishra G and Srinivasan M R. 2017. Beekeeping in India. *Industrial Entomology*. Omkar (Ed.). Springer Nature, Singapore Pte Ltd.
- Tennekes H A and Sanchez-Bayo F. 2012. Time-dependent toxicity of neonicotinoids and other toxicants: implications for a new approach to risk assessment. *Journal of Environmental and Analytical Toxicology* **S4**: S4–001.
- Tijjani A, Bashir K A, Mohammed I, Muhammad A, Gambo A and Musa H. 2016. Biopesticides for pest control: A review. *Journal of Biopesticides and Agriculture* **3**(1): 6–13.
- Whitehorn P R, O'Connor S, Wackers F L and Goulson D. 2012. Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science* **336**: 351–52.