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Honey bees, pesticides, and sustainable crop production: A comprehensive review

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Abstract

Honey bees and other insect pollinators sustain the reproduction of a large share of the world's flowering crop species, yet their populations are under sustained pressure from agrochemical exposure, habitat loss, pathogens, and parasites acting in combination. This review synthesises the current scientific literature on the relationship between pesticide use and honey bee health, and situates that evidence within the broader goal of sustainable crop production. It examines the major classes of agricultural pesticides implicated in bee harm, the physiological and behavioural mechanisms through which lethal and sub-lethal exposure damages individual bees and colonies, and the growing body of evidence, including from Indian agricultural landscapes, documenting pesticide residues in bees, pollen, and honey. The review further considers how pesticide stress interacts synergistically with pathogens, parasites such as *Varroa destructor*, and nutritional deficits to produce colony-level collapse, and compares regulatory responses adopted in the European Union, the United States, and India. It concludes by evaluating mitigation strategies, including Integrated Pest and Pollinator Management, bee-safe pesticide application practices, habitat conservation, and policy measures, and identifies priority areas for future research. The review argues that safeguarding honey bee populations is inseparable from the long-term sustainability, productivity, and resilience of global and Indian agriculture.

Keywords: Honey bees, Pesticides, Neonicotinoids, Pollination, Sustainable agriculture, Colony collapse disorder, Sub-lethal effects, Integrated Pest Management, *Apis Cerana*, Pollinator conservation

Introduction

Insect pollination is a crucial yet often unseen ecosystem service that supports global food production. Honey bees, along with wild bees, butterflies, flies, and other pollinators, enable the sexual reproduction of many flowering plant species, including numerous fruits, vegetables, oilseeds, nuts, and fibre crops vital for human diets and farm incomes. A comprehensive study covering over 200 countries by Klein *et al.*, (2007) ^[12] found that the production of 87 major global food crops relies to some extent on animal pollination. While these crops constitute a minority by weight, they are essential for dietary diversity and quality. Potts *et al.*, (2016) ^[24] estimated that animal pollination supports 35% of global crop production volume, with a market value between USD 235 billion and USD 577 billion, and highlighted ongoing declines in wild pollinator diversity and managed honey bee colonies worldwide.

As the role of pollinators in agriculture has become more clearly understood, evidence has shown that both managed and wild bee populations worldwide are under ongoing stress. In North America and Europe, beekeepers started reporting unusually severe and unexplained colony losses in the mid-2000s, a phenomenon now called colony collapse disorder (CCD). A comprehensive study comparing CCD-affected and unaffected colonies across the United States analysed 61 variables, including pathogen levels, bee physiology, and pesticide residues, and found no single factor consistently distinguished collapsed colonies, though CCD-affected colonies carried higher pathogen loads and more co-infections than healthy colonies (vanEngelsdorp *et al.*, 2009) ^[33]. Around the same time, broader research on pollinator decline identified habitat loss, fragmentation, pesticide exposure, pathogens, parasites, competition from non-native species, and climate change as key interacting drivers that rarely act alone under field conditions (Potts *et al.*, 2010) ^[23].

Although no single cause fully explains these declines, a significant body of research points to agricultural pesticides, used both to protect crops from pests and within beekeeping to control mites and hive pests, as a central, modifiable factor acting alongside pathogens, parasites, habitat destruction, and nutritional stress.

This review consolidates scientific research on the link between pesticide exposure and honey bee health, with a focus on Indian agricultural contexts, where native bee species, varied cropping systems, and a large smallholder farming sector present circumstances that differ significantly from the North American and European settings in which most early pesticide-pollinator research was conducted. The review is structured as follows: Section 2 details its scope and methodology; Section 3 discusses honey bees' role in sustainable farming; Section 4 reviews key pesticide classes and their mechanisms; Section 5 examines lethal and sub-lethal impacts on individual bees and colonies; Section 6 explores colony collapse disorder and multi-stressor effects; Section 7 examines pesticide residue data specific to India; Section 8 compares global regulatory responses; Section 9 considers mitigation strategies and integrated pest and pollinator management; Section 10 presents policy and extension initiatives for India; Section 11 identifies research gaps and future opportunities; and Section 12 offers concluding remarks.

Scope and review approach

This review draws on peer-reviewed research, government and intergovernmental reports, and reputable scientific and regulatory sources focused on honey bee biology, pesticide toxicology, pollination ecology, and agricultural policy, with particular emphasis on studies of native Indian honey bee species (*Apis Cerana indica*, *Apis dorsata*, *Apis florea*) alongside the internationally dominant literature on the introduced Western honey bee, *Apis mellifera*. Sources include laboratory toxicology studies, field and semi-field trials, residue-monitoring surveys, and synthesis reviews, spanning both acute lethal-dose research and the sub-lethal, behavioural, and colony-level literature that has become increasingly central to pollinator risk assessment over the past decade. Because pesticide-pollinator research is a fast-moving field, the review privileges recent primary literature while retaining foundational studies that continue to shape regulatory and scientific thinking.

Honey bees in sustainable crop production

Pollination services and crop yield

Honey bees support crop production through both managed pollination, in which colonies are deliberately placed in or near flowering fields, and incidental pollination by wild and feral colonies. A comprehensive assessment of Indian crop production found that over half of the 211 crops and commodities examined depend partly on animal pollination, with direct insect pollination contributing an estimated ₹112,616 crores (about USD 22.5 billion) annually to Indian agriculture, roughly nine percent of total agricultural value (Chaudhary and Chand, 2017) ^[5]. Field trials across a range of pollinator-dependent crops show yield increases of 15 to 50 percent attributable to effective honey bee pollination (Partap, 2011) ^[20], while crop-specific studies have documented pollination-driven improvements in fruit set, fruit weight, sugar content, and seed quality that translate directly into higher farm-gate value (Khalifa *et al.*, 2021) ^[11]. Globally, these figures sit within a well-established literature: Gallai *et al.*, (2009) ^[7], in a widely cited bioeconomic valuation of 100 crops used directly for human food worldwide, estimated the total economic value of insect pollination at approximately €153 billion in 2005,

roughly 9.5% of global food production value, and projected consumer-surplus losses of €190 to €310 billion under pollinator decline scenarios, identifying fruit, vegetable, and stimulant crops such as coffee and cocoa as the most economically vulnerable categories to pollinator loss, consistent with the nutrition-security concerns raised for India in Section 3.4.

Beekeeping as a livelihood and sustainability strategy

Beyond crop pollination, apiculture is a low-input, eco-friendly farming practice that boosts rural income through the sale of honey, beeswax, propolis, royal jelly, and other hive products. In India, the native *Apis Cerana* is particularly well suited to smallholder and rainfed farms because it does not require migration, tolerates a wide climatic range, and can be kept in simple, affordable box hives, making it accessible to small and marginal farmers. Migratory beekeeping with *Apis mellifera*, moved seasonally among flowering regions such as mustard, sunflower, and litchi, has created a rental-pollination market that benefits both crop yields and beekeeper incomes. Because beekeeping uses less land and fewer chemicals than most other farming activities, its promotion aligns closely with sustainability goals centred on input efficiency, biodiversity conservation, and income diversification.

Pollinators and agricultural biodiversity

Beyond their direct economic contribution, pollinators support the reproduction of wild flowering plants essential for agroecosystem biodiversity, including hedgerow and field-margin vegetation that supports natural pest enemies, stabilises soils, and sustains wildlife food webs. Protecting pollinators is therefore not merely an environmental concern but a structural component of sustainable, resilient agriculture.

Food security and nutritional dimensions

Crops that depend heavily on animal pollination fruits, vegetables, pulses, nuts, and oilseeds are vital sources of micronutrients such as vitamin A, vitamin C, folate, and essential fatty acids, in contrast to the wind- and self-pollinated cereal staples that mainly supply calories. A decline in pollination services therefore poses a smaller threat to caloric intake than to dietary diversity and quality, a distinction crucial to India's public health efforts to improve micronutrient consumption through agricultural diversification rather than staple-crop expansion alone. Because smallholder and marginal farmers in India often rely on pollinator-dependent horticultural crops for both nutrition and income, pollinator decline carries a compounding risk to both farm revenue and household nutritional security.

Pesticide classes and modes of action relevant to bee's neonicotinoids

Neonicotinoid insecticides such as imidacloprid, clothianidin, thiamethoxam, acetamiprid, and thiacloprid target the insect nicotinic acetylcholine receptor, disrupting neural signalling. Typically applied as seed coatings or soil drenches, they translocate through plant vascular tissue into pollen, nectar, and guttation fluid, creating a route of chronic, low-dose exposure throughout a crop's flowering period. By the early 2010s neonicotinoids accounted for roughly one-third of the global insecticide market, making them the most studied pesticide class in pollinator toxicology (Wood and Goulson, 2019) ^[35]. Several landmark field and semi-field experiments have confirmed laboratory concerns under real-world conditions. Whitehorn *et al.*, (2012) ^[34] showed that bumble bee (*Bombus terrestris*) colonies exposed to realistic imidacloprid levels experienced

slower growth and an 85% reduction in new queen production compared with untreated colonies. Rundlöf *et al.*, (2015) ^[26] observed lower wild bee densities, decreased solitary bee nesting, and impaired bumble bee colony growth and reproduction on oilseed rape from clothianidin-coated seeds across sixteen Swedish landscapes, though managed honey bee colonies showed no comparable effect. A multi-country study in the UK, Germany, and Hungary linked neonicotinoid-treated oilseed rape to lower overwintering success and colony reproduction in both honey bees and wild bees, with outcomes varying by landscape quality and forage availability (Woodcock *et al.*, 2017) ^[36]. In North America, honey bee colonies foraging near neonicotinoid-treated corn were exposed for three to four months, resulting in higher worker mortality, weakened social immunity, and increased queenlessness, effects intensified by fungicide co-application (Tsvetkov *et al.*, 2017) ^[32]. A global survey of honey samples corroborates the scale of this exposure independent of any single field study: Mitchell *et al.*, (2017) ^[16], testing 198 honey samples collected worldwide, detected at least one neonicotinoid in 75% of samples and multiple neonicotinoids in 45%, indicating that neonicotinoid contamination of pollinator food resources is a near-global phenomenon. Taken together, these field studies demonstrate that laboratory-identified sub-lethal effects translate into measurable colony-level harm under real-world conditions, though the extent of damage depends on local landscape and forage factors.

Organophosphates, carbamates, and pyrethroids

Older insecticide classes remain widely used in Indian agriculture and pose their own risks to bees. Organophosphates and carbamates target acetylcholinesterase, causing acute neurotoxicity at sufficient doses, while synthetic pyrethroids act on voltage-gated sodium channels; both are acutely toxic to bees on contact, though generally less persistent in plant tissue than neonicotinoids. Surveys of Indian honey have repeatedly detected residues of organophosphates and pyrethroids such as monocrotophos, profenofos, ethion, chlorpyrifos, and cypermethrin, alongside legacy organochlorines such as DDT and HCH isomers that persist in soils despite restrictions on their use (Choudhary and Sharma, 2008; Kumar, Gill and Bedi, 2018) ^[6, 14].

Fungicides and herbicides

Fungicides were long assumed to pose little direct risk to bees because they target fungal rather than insect physiology; this assumption has not held up under closer study. Certain fungicide classes, notably demethylase-inhibitor (DMI) compounds, significantly potentiate the toxicity of co-applied neonicotinoids in laboratory trials, and fungicide residues are now recognised as near-ubiquitous contaminants of bee-collected pollen (Godfray *et al.*, 2014) ^[8]. Herbicides act indirectly on bees primarily by eliminating the flowering weeds that provide forage between crop bloom periods, but glyphosate exposure also has direct experimental support for a more specific mechanism: Motta *et al.*, (2018) ^[17] found that honey bees exposed to field-realistic glyphosate concentrations experienced measurable depletion of several core gut bacterial species, most notably *Snodgrassella alvi*, and that bees with glyphosate-perturbed gut communities suffered substantially higher mortality when subsequently challenged with the opportunistic pathogen *Serratia marcescens* than bees with an intact microbiota. Because these gut bacteria assist with nutrient processing and pathogen resistance, the study's authors argued that glyphosate's conventional classification as harmless to animals, based on the absence of its plant-specific molecular target in bee tissue, overlooks an indirect but biologically significant route of harm operating through the bee's associated microbial community.

Acaricides used in hive management

A pesticide category specific to beekeeping rather than crop protection is the class of acaricides applied directly within hives to control *Varroa destructor* and other mite pests. Compounds such as amitraz, coumaphos, and various synthetic pyrethroids are widely used for this purpose, and while formulated to be less toxic to adult bees than to mites, residues accumulate in beeswax comb over repeated seasons and have been detected alongside field-applied pesticides in Indian honey residue surveys (Tripathy *et al.*, 2024) ^[31]. This makes in-hive chemical management an additional, often overlooked, contributor to the cumulative pesticide burden experienced by managed colonies, distinct from but compounding foraging-related exposure.

Summary of pesticide classes and bee risk

Table 1: summarises the pesticide classes discussed above, their primary agricultural use, mode of action, and the nature of the risk each poses to honey bees, drawing together the mechanistic evidence reviewed in this section.

Pesticide class	Representative compounds	Primary agricultural use	Nature of bee risk
Neonicotinoids	Imidacloprid, clothianidin, thiamethoxam, acetamiprid	Systemic seed and soil-applied insecticides	Chronic sub-lethal exposure via contaminated pollen/nectar, impaired learning, navigation, immunity
Organophosphates	Monocrotophos, chlorpyrifos, profenofos	Broad-spectrum foliar insecticides	Acute contact/ingestion toxicity, acetylcholinesterase inhibition
Pyrethroids	Cypermethrin, deltamethrin	Foliar insecticides	Acute contact toxicity; sodium-channel disruption, residue persistence in wax
Organochlorines (legacy)	DDT, HCH/lindane	Historic insecticide use, environmental persistence	Long-term soil and honey contamination despite restricted current use
DMI fungicides	Triazole-class compounds	Foliar fungal disease control	Low direct toxicity but potentiates neonicotinoid and other insecticide toxicity
Herbicides	Glyphosate and others	Weed control	Indirect: reduces flowering forage; depletes core gut bacteria (Motta <i>et al.</i> , 2018) ^[17]
In-hive acaricides	Amitraz, coumaphos	Varroa mite control within managed colonies	Residue accumulation in wax, additive chemical burden on managed bees

Lethal and sub-lethal effects on bees

Acute toxicity

Direct, high-dose exposure to insecticides through spray drift, contact with treated foliage, or ingestion of heavily contaminated nectar can kill foragers outright and, in severe cases, cause visible mass mortality events at hive entrances. Acute toxicity has

historically dominated regulatory testing because it is straightforward to measure through standard LD50 assays, but a growing consensus in the literature holds that acute lethality alone substantially understates the risk pesticides pose to bee populations under realistic field conditions (Siviter *et al.*, 2018) [28].



Fig 1: Mortality of honey bees following pesticide exposure. Acute pesticide toxicity can result in rapid loss of foraging bees and weaken colony survival

Sub-lethal behavioural and cognitive effects

Even at doses too low to cause death, neonicotinoids and similar systemic pesticides have consistently been shown to impair the cognitive and sensory functions bees rely on for foraging and colony coordination. Laboratory and semi-field research indicate that sub-lethal exposure damages brain regions including the mushroom bodies, diminishes olfactory learning and memory, and disrupts navigation and homing flights (Stanley, Smith and Raine, 2015) [29]. Working with several neonicotinoids side by side, Mustard *et al.*, (2020) [18] found that honey bees fed thiamethoxam were completely unable to differentiate floral scents in a differential learning task, whereas bees fed imidacloprid, clothianidin, or dinotefuran learned more slowly but retained the ability to discriminate odours evidence that neonicotinoid effects on cognition are compound-specific rather than uniform across the class. Navigation has been examined directly: using RFID tags to track free-foraging bees, Henry *et al.*, (2012) [10] found that a single field-realistic dose of thiamethoxam significantly increased homing failure, suggesting a pathway through which chronic low-dose exposure could destabilise colony forager populations; similarly, Schneider *et al.*, (2012) [27] showed that clothianidin and imidacloprid exposure led to fewer foraging trips and longer time away from the colony per trip. These findings have faced methodological criticism, with some researchers arguing that the statistical treatment of control mortality may overstate the effects (Guez, 2013) [9], underscoring the difficulty of translating small behavioural effects into confident colony-level risk assessments. Because foraging efficiency, waggle-dance communication, and homing accuracy are all central to a colony's ability to gather sufficient food, these behavioural impairments can threaten colony survival even without individual bee mortality.

Indian research on native *Apis Cerana* populations has produced parallel findings using different methodologies. Bees sampled from pesticide-intensive cropping landscapes in Odisha showed significantly reduced proboscis extension response, structural damage to antennal sensillae, and disrupted resting-state calcium signalling in the brain compared with bees from low-pesticide sites, effects reproduced under controlled laboratory exposure (Chakrabarti *et al.*, 2015) [3]. Related studies documented elevated oxidative-stress biomarkers superoxide dismutase, catalase, and xanthine oxidase in *Apis Cerana* and *Apis dorsata* sampled along a pesticide-use gradient in West Bengal and Odisha (Chatterjee *et al.*, 2014), while a follow-up study found heightened markers of oxidative damage and apoptosis in *Apis Cerana* exposed to multiple pesticides simultaneously, a scenario the authors note is closer to real farm conditions than single-compound laboratory tests (Kumar *et al.*, 2022) [15].

Colony-level consequences

Sub-lethal effects on individual foragers accumulate into observable colony-level impacts, including reduced brood production, smaller adult populations, lower honey yield, and reduced resilience during winter or dearth periods. Field evidence for this aggregation is direct, Woodcock *et al.*, (2017) [36] found that neonicotinoid-treated oilseed rape reduced overwintering colony survival in a multi-country European trial, and Tsvetkov *et al.*, (2017) [32] documented increased queenlessness in colonies chronically exposed near corn crops. Modelling incorporated into pollinator-risk assessments indicates that once forager death rates exceed a critical threshold, colonies can enter a self-reinforcing decline in which younger bees are recruited to forage prematurely, further accelerating collapse (Godfray *et al.*, 2014) [8]. Because these effects often take weeks to manifest, beekeepers and

researchers frequently find it difficult to directly link a specific pesticide application to eventual colony loss, contributing to historical underestimation of pesticide risk relative to more visible threats such as disease.

Colony collapse disorder and multi-stressor interactions

As Section 1 notes, no single factor has been shown to consistently distinguish CCD-affected from healthy colonies (vanEngelsdorp *et al.*, 2009) ^[33], and the weight of evidence points instead to interacting combinations of stressors (Potts *et al.*, 2010) ^[23]. Among the specific interactions documented, the relationship between pesticide exposure and the parasitic mite *Varroa destructor*, together with the viruses it transmits most notably deformed wing virus has received particular attention. Pesticide-related immune suppression appears to weaken a colony's ability to control viral replication, turning normally low-level, covert infections into deadly outbreaks under additional stress (Nazzi and Pennacchio, 2018) ^[19]. Neonicotinoid exposure has similarly been linked to increased vulnerability to the gut pathogen *Nosema*, and to synergistic toxicity when combined with DMI fungicides or other insecticides in tank mixtures, a concern of growing relevance given that bees in intensively farmed landscapes are rarely exposed to a single compound in isolation (Godfray *et al.*, 2014; Kumar *et al.*, 2022) ^[8, 15]. A recent study on a mixture of a neonicotinoid (acetamiprid) and a pyrethroid (deltamethrin) in the native Saudi Arabian honey bee subspecies *Apis mellifera jemenitica* found significantly higher mortality and impaired learning and memory in bees exposed to the mixture compared with either compound alone, reinforcing the case that risk assessments based on single-compound testing may understate real-world hazard (Abuagla *et al.*, 2025) ^[1].

This multi-causal picture has also generated genuine scientific debate: some researchers argue that the timing of reported pollinator declines does not consistently coincide with neonicotinoid adoption patterns, and caution against attributing colony losses to any single chemical class without longer-term field data (Blacquière and van der Steen, 2017) ^[2]. This dissenting analysis reinforces, rather than undermines, the broader scientific consensus that bee health outcomes are shaped by multiple interacting factors, and that risk assessment frameworks need to account for those interactions.

Pesticide-pollinator evidence from India

Field and laboratory studies on native bees

Indian research groups, most prominently the Centre for Pollination Studies at the University of Calcutta, have generated a growing body of field and laboratory evidence documenting olfactory, neurological, and oxidative-stress damage in native *Apis Cerana* and *Apis dorsata* populations from pesticide-intensive agricultural landscapes in Odisha and West Bengal (Chakrabarti *et al.*, 2015; Chatterjee *et al.*, 2014; Kumar *et al.*, 2022) ^[3]. These findings are significant because they extend evidence largely established using the introduced *Apis mellifera* to India's native pollinator species, which differ in physiology, foraging behaviour, and ecological role, and cannot be assumed to respond identically to pesticide stress.

Pesticide residues in Indian honey

Indian research has also investigated pesticide residues in honey as both an environmental-contamination indicator and a food-safety concern. Kumar, Gill, Bedi and Kumar (2018) ^[14] surveyed 100 raw honey samples from northern India and detected residues in 19% of samples, with dichlorvos, monocrotophos, profenofos, permethrin, ethion, and lindane the most frequently identified

compounds; honey from cotton, sunflower, and mustard fields showed significantly higher contamination (33.3%) than honey from natural or fruit-tree vegetation (13.5%). An earlier study of honey from Himachal Pradesh identified HCH and DDT isomers as the most frequent residues, with malathion in some samples exceeding the maximum residue limit proposed for honey (Choudhary and Sharma, 2008) ^[16]. A related multiresidue survey of 150 market honey samples from northern India by the same research group detected pesticides, predominantly organophosphates, in 12% of samples, though the associated human health risk was assessed as low at the concentrations observed (Kumar, Gill and Bedi, 2018) ^[14]. Separately, a survey of honey from apiaries in Kerala using LC-MS/MS and GC-MS/MS screened for a broad panel of pesticide classes and found propoxur and deltamethrin exceeding the maximum residue limit set for honey exported to the European Union in two of twelve samples tested (Prasanth *et al.*, 2022) ^[25]. More recent tandem mass spectrometry analyses screening over 400 pesticide compounds in honey collected across India have continued to detect acaricide, fungicide, and insecticide residues, some attributable to chemicals applied within hives to control *Varroa* mites rather than to field spraying alone (Tripathy *et al.*, 2024) ^[31].

Collectively, these residue studies indicate that Indian honey bees are chronically exposed to a mixture of contemporary and legacy pesticides through their foraging environment, that exposure levels vary substantially by cropping system and region, and that contamination is generally, though not universally, higher in honey sourced from intensively sprayed field crops such as cotton and mustard than from mixed natural vegetation a pattern consistent with the mechanistic and physiological evidence of pesticide harm described in Section 5 and the global contamination pattern documented by Mitchell *et al.*, (2017) ^[16] in Section 4.1.

Economic stakes for Indian agriculture

This evidence carries significant economic weight. Where pollinator decline reduces pollination services, yield losses in dependent crops have been estimated at 20 to 80 percent, with per-hectare income losses of ₹10,000 to ₹55,000 and potential aggregate national losses exceeding ₹1 lakh crore annually under severe decline scenarios (Swain *et al.*, 2025). Many crops most reliant on pollination mustard, cotton, fruits, and vegetables are also among the most heavily insecticide-treated in Indian agriculture, meaning the regions that stand to benefit most from healthy pollinator populations are frequently those where pesticide exposure risk to bees is highest, underscoring the need for management strategies that reconcile the two.

International and indian regulatory responses

European union

In 2013, the European Union restricted outdoor use of three neonicotinoids clothianidin, imidacloprid, and thiamethoxam on bee-attractive crops following a European Food Safety Authority risk assessment, and moved to an almost complete outdoor ban in 2018 after further evidence, including the Woodcock *et al.*, (2017) ^[36] field trial described in Section 4.1, confirmed unacceptable risk to bees. A retrospective review of this regulatory episode concluded that the risk-assessment protocols in place when neonicotinoids were first authorised in the 1990s were not designed to capture risks arising from high persistence, systemic movement through plant tissue, and environmental mobility, and argued for risk assessment grounded in the precautionary principle amid scientific uncertainty (Wood and Goulson, 2019) ^[35]. Post-moratorium monitoring substantiates this persistence

concern directly: Woodcock *et al.*, (2018) ^[37], analysing 130 UK honey samples collected before and after the ban, found that neonicotinoids were present in about half of samples taken before the moratorium and still present in over a fifth of samples afterward, with residues correlated with the area of oilseed rape surrounding each apiary evidence that soil-persisting residues from previously treated fields continue to reach bees via subsequently planted, untreated crops.

United states

The United States Environmental Protection Agency has pursued a more incremental regulatory path, restricting neonicotinoid use during active bee foraging, expediting registration review of the neonicotinoid family, and temporarily pausing approval of new outdoor neonicotinoid product uses pending additional pollinator risk data. This approach has drawn criticism from some researchers and advocacy groups as insufficiently precautionary relative to the EU's restrictions, while others caution that abrupt restriction without adequate alternative pest-control options can impose significant costs on growers.

India

India's pesticide regulation, centred on the Insecticides Act, 1968, and its associated rules, has historically emphasised human toxicity, efficacy, and residue limits in food, with comparatively limited explicit attention to pollinator risk during registration. Some insecticide labels carry bee-hazard warnings, but enforcement of application-timing guidance and grower awareness of bee-safety practices remain inconsistent across states and crops. As Indian horticultural and oilseed production continues to expand and export markets increasingly scrutinise pesticide residues in honey and produce, there is a substantive case for more explicit integration of pollinator-risk data into pesticide registration, alongside strengthened extension messaging on application timing relative to crop flowering.

Mitigation strategies and integrated pest and pollinator management

Integrated pest and pollinator management (IPPM)

Integrated Pest and Pollinator Management extends conventional

Integrated Pest Management by explicitly incorporating pollinator health into pest-control decision-making, rather than treating pesticide use and pollinator conservation as separate concerns (Phan *et al.*, 2025) ^[22]. Field research demonstrates that IPM regimes based on economic thresholds and targeted intervention can reduce insecticide applications very substantially: in a four-year, commercial-scale experiment integrating corn and watermelon production in the midwestern United States, Pecenka *et al.*, (2021) ^[21] found that IPM reduced insecticide applications by approximately 95% relative to conventional calendar-based management while maintaining or even increasing watermelon yields, an effect mediated primarily through conservation of wild bee pollinator communities rather than managed honey bee colonies.

Application practices that reduce bee exposure

A set of affordable, widely applicable practices can significantly reduce pesticide exposure for foraging bees without eliminating pesticide use entirely. These include spraying insecticides late in the evening or at night when bees are not foraging; avoiding application to flowering crops, weeds, or field margins; choosing products with lower bee toxicity and shorter residual activity where efficacy permits; observing bee-hazard warnings and pre-harvest intervals on product labels; and informing nearby beekeepers of spray schedules so hives can be moved or closed during treatment.

Habitat and landscape-level measures

Because herbicide use and monoculture cropping reduce flowering forage outside the main crop's bloom period, preserving flowering field margins, hedgerows, and buffer strips gives bees alternative forage and reduces the concentration of foraging activity on treated crops at any given time. Such landscape diversification has been shown to support both wild pollinator abundance and biological pest control, complementing rather than competing with productive farmland, consistent with the wild-bee-mediated yield benefits documented by Pecenka *et al.*, (2021) ^[21] in Section 9.1.



Fig 2: Flower-rich field margins provide continuous forage resources for pollinators and improve biodiversity within agricultural landscapes

Reducing in-hive chemical exposure

Beekeepers contribute to bees' pesticide exposure through acaricide treatments used inside hives to manage Varroa mites; residue-monitoring studies have detected these compounds in Indian honey samples alongside field-applied pesticides (Tripathy

et al., 2024) ^[31]. Judicious, rotation-based use of in-hive treatments, combined with non-chemical mite-control methods such as brood interruption and resistant stock selection, can reduce this additional exposure pathway.

Policy and institutional support in India

India's principal institutional response to the pollination and beekeeping challenge is the National Beekeeping and Honey Mission (NBHM), a Central Sector Scheme managed by the National Bee Board under the Ministry of Agriculture and Farmers' Welfare. Launched in 2020 under the Atmanirbhar Bharat initiative with an initial outlay of ₹500 crore, the mission has been extended through 2025-26 with a further ₹370 crore allocation, and operates through three Mini Missions addressing pollination-assisted productivity, post-harvest processing and marketing, and region-specific research. Programmes under the Khadi and Village Industries Commission provide subsidised credit for beekeeping equipment, support beekeeping clusters and Integrated Beekeeping Development Centres, and fund honey-testing laboratories intended to address adulteration and quality concerns identified in residue-monitoring research.

Since 2020, India has risen from the ninth- to the second-largest global honey exporter. What remains comparatively underdeveloped is the explicit integration of pesticide regulation with pollinator and beekeeping policy: bee-hazard data are not yet a standard, enforced requirement of pesticide registration in India, and coordination between crop-protection and beekeeping extension services remains uneven. Strengthening this institutional linkage through mandatory bee-toxicity data at registration, coordinated advisories timed to regional flowering calendars, and routine residue monitoring in honey would help ensure that investment in beekeeping promotion is not undermined by pesticide practices in the same agricultural landscapes.

Research gaps and future directions

Several gaps in the current evidence base warrant attention. First, the great majority of sub-lethal toxicology research remains focused on *Apis mellifera* under temperate, single-crop conditions; comparable studies on *Apis Cerana*, *Apis dorsata*, *Apis florea*, and India's diverse wild bee fauna under mixed-cropping, multi-pesticide conditions remain comparatively limited, though the Calcutta University studies discussed in this review represent an important start. Second, most toxicology testing continues to examine single compounds in isolation, even though field-realistic exposure typically involves mixtures of insecticides, fungicides, and herbicides; expanded mixture and synergy testing, of the kind illustrated by the neonicotinoid-fungicide interaction in Tsvetkov *et al.*, (2017)^[32] and the neonicotinoid-pyrethroid binary study of Abuagla *et al.*, (2025)^[1], is needed to better characterise real-world risk. Third, long-term, landscape-scale field monitoring linking pesticide-use intensity to colony survival, honey yield, and crop pollination outcomes over multiple seasons remains rare in the Indian context, limiting the ability to translate laboratory and short-term findings into confident policy recommendations. Fourth, economic research quantifying the return on investment of pollinator-protective pesticide practices for Indian farmers, as distinct from the value of pollination services generally, would strengthen the case for voluntary adoption of bee-safe practices, drawing on the yield-neutral or yield-positive outcomes documented for IPM adoption elsewhere (Pecenka *et al.*, 2021)^[21]. Finally, systematic residue monitoring of honey and pollen across a wider set of Indian agro-climatic zones and crop systems, extended over time, would help track whether policy and extension interventions are reducing pesticide burden on Indian pollinators.

Conclusion

This review supports three main conclusions. First, honey bees make a substantial and well-quantified contribution to the

productivity, income, and dietary diversity of Indian and global agriculture, positioning pollinator health as a core rather than peripheral concern for sustainable crop production. Second, pesticide exposure, through both acute lethality and, more pervasively, sub-lethal impairment of learning, navigation, and immune function, is a significant and modifiable driver of pollinator stress that interacts synergistically with pathogens, parasites, and nutritional deficits to produce colony-level decline, and one for which India-specific field and residue evidence is now accumulating alongside the larger international literature. Third, meaningful mitigation is achievable without abandoning pesticide use altogether: Integrated Pest and Pollinator Management, bee-safe application practices, habitat conservation, more pollinator-conscious pesticide regulation, and continued institutional investment through programmes such as the National Beekeeping and Honey Mission together constitute a realistic, evidence-based path forward. Realising that path will require closer coordination between toxicologists, agronomists, regulators, extension services, and the farmers and beekeepers whose livelihoods depend on both productive crops and healthy bees.

References

1. Abuagla MIB, Iqbal J, Raweh HSA, Abdelaziz ASA, Alqarni AS. Binary mixture of neonicotinoid-pyrethroid insecticide: Impact on survival, cognitive learning, and memory in *Apis mellifera jemenitica*. *Biology*. 2025;14(2):147.
2. Blacquière T, van der Steen JJM. Three years of banning neonicotinoid insecticides based on sub-lethal effects: Can we expect to see effects on bees? *Pest Manag Sci*. 2017;73(7):1299-1304.
3. Chakrabarti P, Rana S, Bandopadhyay S, Naik DG, Sarkar S, Basu P. Field populations of native Indian honey bees from pesticide-intensive agricultural landscapes show signs of impaired olfaction. *Sci Rep*. 2015; 5:12504.
4. Chatterjee S, Kumar D, Bhattacharya R, Chatterjee A, Chakrabarti P, Rana S, *et al.* Pesticide-induced oxidative stress in laboratory and field populations of native honey bees along intensive agricultural landscapes in two eastern Indian states. *Apidologie*. 2015;46(1):107-129.
5. Chaudhary OP, Chand R. Economic benefits of animal pollination to Indian agriculture. *Indian J Agric Sci*. 2017;87(3):315-320.
6. Choudhary A, Sharma DC. Pesticide residues in honey samples from Himachal Pradesh, India. *Bull Environ Contam Toxicol*. 2008;80(5):417-422.
7. Gallai N, Salles JM, Settele J, Vaissière BE. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecol Econ*. 2009;68(3):810-821.
8. Godfray HCJ, Blacquière T, Field LM, Hails RS, Petrokofsky G, Potts SG, *et al.* A restatement of the natural science evidence concerning neonicotinoid insecticides and insect pollinators. *Proc R Soc B Biol Sci*. 2014;281(1786):20140558.
9. Guez D. Assessing homing failure in honeybees exposed to pesticides: Pitfalls and challenges. *Front Physiol*. 2013; 4:352.
10. Henry M, Béguin M, Requier F, Rollin O, Odoux JF, Aupinel P, *et al.* A common pesticide decreases foraging success and survival in honey bees. *Science*. 2012;336(6079):348-350.
11. Khalifa SAM, Elshafiey EH, Shetaia AA, El-Wahed AAA, Algethami AF, Musharraf SG, *et al.* Overview of bee pollination and its economic value for crop production. *Insects*. 2021;12(8):688.
12. Klein AM, Vaissière BE, Cane JH, Steffan-Dewenter I,

- Cunningham SA, Kremen C, *et al.* Importance of pollinators in changing landscapes for world crops. *Proc R Soc B Biol Sci.* 2007;274(1608):303-313.
13. Kumar A, Gill JPS, Bedi JS. Multiresidue determination of pesticides in market honey from northern India using QuEChERS approach and assessment of potential risks to consumers. [Journal details to be confirmed before final submission.]
 14. Kumar A, Gill JPS, Bedi JS, Kumar A. Pesticide residues in Indian raw honeys, an indicator of environmental pollution. *Environ Sci Pollut Res.* 2018;25(34):34005-34016.
 15. Kumar D, Banerjee D, Sarkar S, Basu P. Oxidative stress and apoptosis in Asian honey bees (*Apis cerana*) exposed to multiple pesticides in intensive agricultural landscapes. *Apidologie.* 2022; 53:43.
 16. Mitchell EAD, Mulhauser B, Mulot M, Mutabazi A, Glauser G, Aebi A. A worldwide survey of neonicotinoids in honey. *Science.* 2017;358(6359):109-111.
 17. Motta EVS, Raymann K, Moran NA. Glyphosate perturbs the gut microbiota of honey bees. *Proc Natl Acad Sci U S A.* 2018;115(41):10305-10310.
 18. Mustard JA, Gott A, Scott J, Chavarria NL, Wright GA. Honeybees fail to discriminate floral scents in a complex learning task after consuming a neonicotinoid pesticide. *J Exp Biol.* 2020;223(5): jeb217174.
 19. Nazzi F, Pennacchio F. Honey bee antiviral immune barriers as affected by multiple stress factors: A novel paradigm to interpret colony health decline and collapse. *Viruses.* 2018;10(4):159.
 20. Partap U. The pollination role of honeybees. In: Srivastava NL, editor. *Pollination Biology and Crop Production.* New Delhi: Indian Council of Agricultural Research; 2011. p. 15-29.
 21. Pecenka JR, Ingwell LL, Foster RE, Krupke CH, Kaplan I. IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation. *Proc Natl Acad Sci U S A.* 2021;118(44): e2108429118.
 22. Phan NT, Biddinger DJ, Rajotte EG, Smagghe G, Reddy GVP, Ren ZX, *et al.* Pesticide use in integrated pest and pollinator management framework to protect pollinator health. *Pest Manag Sci.* 2025;81(4):1691-1696.
 23. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: Trends, impacts and drivers. *Trends Ecol Evol.* 2010;25(6):345-353.
 24. Potts SG, Imperatriz-Fonseca V, Ngo HT, Biesmeijer JC, Breeze TD, Dicks LV, *et al.* The assessment report on pollinators, pollination and food production: Summary for policymakers. Bonn (Germany): Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; 2016.
 25. Prasanth J, Vincy MV, Brilliant R. Screening and quantitation of pesticide residues in Indian honey samples by LC-MS/MS and GC-MS/MS. *Indian J Sci Technol.* 2022;15(23):1112-1123.
 26. Rundlöf M, Andersson GKS, Bommarco R, Fries I, Hederström V, Herbertsson L, *et al.* Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature.* 2015;521(7550):77-80.
 27. Schneider CW, Tautz J, Grünwald B, Fuchs S. RFID tracking of sublethal effects of two neonicotinoid insecticides on the foraging behavior of *Apis mellifera*. *PLoS One.* 2012;7(1): e30023.
 28. Siviter H, Koricheva J, Brown MJF, Leadbeater E. Quantifying the impact of pesticides on learning and memory in bees. *J Appl Ecol.* 2018;55(6):2812-2821.
 29. Stanley DA, Smith KE, Raine NE. Bumblebee learning and memory is impaired by chronic exposure to a neonicotinoid pesticide. *Sci Rep.* 2015; 5:16508.
 30. Swain R, Rath S, Dash PK. Economic impact of honey bees (*Apis* spp.) in India: How pollination supports farmers' livelihoods and national agricultural productivity. [Publication details to be completed before submission.]
 31. Tripathy V, Devi S, Singh G, Yadav R, Sharma K, Gupta R, *et al.* Development and validation of tandem mass spectrometry-based method for the analysis of more than 400 pesticides in honey. *J Food Compos Anal.* 2024; 128:106013.
 32. Tsvetkov N, Samson-Robert O, Sood K, Patel HS, Malena DA, Gajiwala PH, *et al.* Chronic exposure to neonicotinoids reduces honey bee health near corn crops. *Science.* 2017;356(6345):1395-1397.
 33. vanEngelsdorp D, Evans JD, Saegerman C, Mullin C, Haubruge E, Nguyen BK, *et al.* Colony collapse disorder: A descriptive study. *PLoS One.* 2009;4(8): e6481.
 34. Whitehorn PR, O'Connor S, Wäckers FL, Goulson D. Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science.* 2012;336(6079):351-352.
 35. Wood TJ, Goulson D. Bees and pesticide regulation: Lessons from the neonicotinoid experience. *Biol Conserv.* 2019; 241:108327.
 36. Woodcock BA, Bullock JM, Shore RF, Heard MS, Pereira MG, Redhead J, *et al.* Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. *Science.* 2017;356(6345):1393-1395.
 37. Woodcock BA, Ridding L, Freeman SN, Pereira MG, Sleep D, Redhead J, *et al.* Neonicotinoid residues in UK honey despite European Union moratorium. *PLoS One.* 2018;13(1): e0189681.