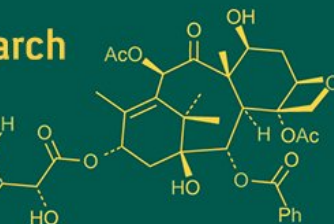
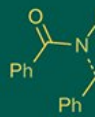


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Pollination ecology and crop yield: A review on the comparative efficiency of managed honey bees and wild pollinators in central India

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Abstract

Pollination represents one of the most critical ecosystem services supporting global agricultural productivity and food security. In Central India, where agriculture constitutes the backbone of rural livelihoods and supports over 42% of the population, understanding the comparative efficiency of managed honey bees (*Apis mellifera* and *Apis cerana*) versus wild pollinators is essential for optimizing crop yields and ensuring sustainable farming practices. This comprehensive review synthesizes current knowledge on pollination ecology in Central India, examining the relative contributions of managed and wild pollinators to crop production across diverse agroecosystems including intensive agricultural plains, forest-agriculture mosaics and mixed farming systems. The analysis reveals that while managed honey bees, particularly *Apis mellifera*, remain the primary focus of commercial pollination services due to their colony strength, manageability and higher honey yields, wild pollinators including stingless bees (*Tetragonula iridipennis*), carpenter bees (*Xylocopa* spp.), blue-banded bees (*Amegilla* spp.), leafcutter bees (*Megachile* spp.) and diverse solitary bee species contribute significantly to pollination networks and often demonstrate superior efficiency on a per-visit basis. Studies indicate that wild pollinators provide crucial insurance against pollination deficits during periods when managed colonies underperform due to disease, adverse weather conditions, or management issues. The economic value of pollination services in India has been estimated at Rs. 266.33 thousand crore annually (2021-22), representing approximately 8-10% of total crop output value, with oilseeds, fruits and vegetables showing the highest dependence on pollinator services. However, pollinator populations face mounting threats from habitat fragmentation, indiscriminate pesticide use particularly neonicotinoid insecticides, climate change-induced phenological mismatches and disease prevalence including *Varroa destructor* mites and viral infections. This review critically examines existing research gaps, methodological approaches for assessing pollinator efficiency, the interactive effects of managed and wild pollinators and the implications of pollinator decline for Central Indian agriculture. Future research priorities include long-term monitoring of pollinator communities using standardized protocols, evaluation of synergistic effects between managed and wild pollinators, development of pollinator-friendly agricultural practices including Integrated Pest and Pollinator Management (IPPM) strategies and policy interventions supporting sustainable pollination services. The findings underscore the urgent need for conservation initiatives that protect wild pollinator habitats while optimizing managed pollination services to ensure food security, nutritional adequacy and agricultural sustainability in Central India.

Keywords: Pollination ecology, Managed honey bees, Wild pollinators, *Apis mellifera*, *Apis cerana*, Crop yield, Central India, Pollinator efficiency, Agricultural ecosystems, Pollinator conservation, Stingless bees, Ecosystem services, Food security, Sustainable agriculture

1. Introduction

1.1 Background and significance of pollination ecology

Pollination constitutes a fundamental ecological process that underpins agricultural productivity, biodiversity conservation and ecosystem stability worldwide. Approximately 87.5% of flowering plant species depend to varying degrees on animal-mediated pollination, with insects serving as the primary vectors for pollen transfer across terrestrial ecosystems (Ollerton *et al.* 2011) [18]. The intricate relationships between flowering plants and their pollinators have evolved over millions of years, resulting in complex networks of mutual dependencies that support the functioning of both natural and agricultural ecosystems. In agricultural contexts, animal pollination directly influences the yield and quality of

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The significance of pollination services becomes particularly pronounced in developing nations where agricultural systems remain heavily dependent on ecosystem services and where smallholder farming predominates. In these regions, the loss of pollinator populations can have immediate and severe consequences for food security, nutritional adequacy and rural livelihoods. The decline of pollinator populations observed in various parts of the world has therefore emerged as a critical concern for agricultural sustainability and global food systems. This decline, driven by multiple interacting factors including habitat loss, pesticide exposure, climate change and disease, threatens to undermine the ecosystem services upon which agricultural productivity depends. India, as one of the world's largest agricultural producers and home to over 1.4 billion people, hosts remarkable pollinator diversity encompassing more than 800 bee species alongside numerous butterflies, moths, beetles, flies, birds and bats that contribute to crop and wild plant pollination (Ministry of Statistics & Programme Implementation, 2026) ^[15]. The country's diverse agroecological zones, ranging from the Himalayan foothills to the coastal plains, support distinct pollinator communities adapted to local environmental conditions and cropping systems. The economic valuation of pollination services in Indian agriculture has demonstrated substantial growth, increasing from Rs. 115.41 thousand crore in 2012-13 to Rs. 266.33 thousand crore in 2021-22, representing approximately 8-10% of total crop output value (MoSPI, 2026) ^[15]. This valuation underscores the critical importance of pollinators for national food security, nutritional adequacy and rural livelihood sustainability.

1.2 Central india: agroecological context and significance

Central India, comprising the states of Madhya Pradesh and Chhattisgarh along with adjoining regions of Maharashtra and Uttar Pradesh, represents a distinctive agroecological zone characterized by diverse cropping systems, varying climatic conditions and heterogeneous landscapes ranging from intensive agricultural plains to forest-agriculture mosaics. The region experiences a tropical monsoon climate with distinct wet and dry seasons, creating seasonal patterns of floral resource availability that influence pollinator community dynamics. The agricultural systems of Central India are predominantly rainfed, with kharif (monsoon) crops including soybean, cotton, pulses and oilseeds forming the backbone of production, supplemented by rabi (winter) crops such as wheat, gram and mustard. The region's agricultural economy depends substantially on pollinator-dependent crops including oilseeds (mustard, sunflower, sesame, niger), pulses (pigeon pea, green gram), vegetables (cucurbits, solanaceous crops, leguminous vegetables) and fruit crops (mango, citrus, guava). Madhya Pradesh alone accounts for significant production of mustard, sunflower and various pulse crops, all of which demonstrate high dependence on insect pollination. Despite this dependence, systematic research on pollination ecology and the comparative efficiency of different pollinator groups remains limited in Central India compared to other regions of the country such as the Western Ghats, Himalayan states, or the Indo-Gangetic plains.

The landscape context of Central Indian agriculture presents both challenges and opportunities for pollinator conservation. The region retains significant forest cover in

many areas, creating potential habitat for wild pollinators and supporting landscape connectivity. However, agricultural intensification, expansion of monoculture systems and increasing pesticide use threaten to degrade pollinator habitats and reduce the diversity of pollination services available to crops. Understanding the current status of pollinator communities and their contributions to crop production is therefore essential for developing region-specific management recommendations.

1.3 Managed honey bees: historical context and current status

The practice of managed beekeeping in India dates back centuries, with the indigenous honey bee *Apis cerana indica* (Fabricius) being traditionally maintained in log hives, wall cavities and wooden boxes across the subcontinent. Traditional beekeeping practices have been particularly prevalent in forested areas and tribal communities, where honey hunting and rudimentary hive management have provided supplementary income and nutritional resources. The knowledge systems associated with traditional beekeeping reflect deep understanding of local bee behavior, seasonal cycles and floral resources.

The introduction of the European honey bee *Apis mellifera* Linnaeus during the 1960s marked a significant transformation in Indian apiculture, particularly in northern and subsequently southern states (Abrol, 2007) ^[1]. *Apis mellifera* was successfully established in the foothills of Himachal Pradesh and the agricultural plains of Punjab, from where it spread to become the dominant species for commercial beekeeping across much of India. The introduction was driven by expectations of higher honey yields and the availability of established management technologies developed in Western countries. The species' popularity stems from its higher honey yields (averaging 25 kg per colony annually compared to 6.5 kg for *A. cerana*), greater colony strength, easier manageability and reduced tendency for absconding during dearth periods (Dalio, 2015) ^[5].

However, the dominance of *Apis mellifera* in managed pollination systems has raised important questions regarding its comparative efficiency relative to native pollinator species, its ecological impacts on native bees and the sustainability of relying on a single introduced species for pollination services. Concerns have been raised about potential competition between *A. mellifera* and native bee species for floral resources, the spread of diseases from managed to wild populations and the genetic integrity of native *A. cerana* populations. These concerns have prompted calls for more balanced approaches that integrate both managed and wild pollinators into agricultural pollination strategies.

1.4 Wild pollinators: diversity and ecological importance

Wild pollinators encompass a taxonomically diverse assemblage of insects and other animals that provide pollination services without direct human management. In India, this category includes native honey bee species such as *Apis dorsata* (the rock bee), *Apis florea* (the little bee) and *Apis andreniformis*; stingless bees belonging to the genus *Tetragonula* and related genera; solitary bees including carpenter bees (*Xylocopa* spp.), leafcutter bees (*Megachile* spp.), blue-banded bees (*Amegilla* spp.), halictid bees and numerous other families; along with non-bee

pollinators such as butterflies, moths, beetles and syrphid flies (Belavadi & Ganeshaiah, 2013) ^[3]. Each of these groups exhibits distinct foraging behaviors, floral preferences and pollination efficiencies that collectively contribute to the functional diversity of pollination networks.

The ecological importance of wild pollinators extends beyond their direct contribution to crop pollination. These species maintain pollination services for wild plant communities, thereby supporting ecosystem structure and function, biodiversity conservation and the provision of other ecosystem services. Furthermore, wild pollinators often exhibit greater floral constancy, specialized behaviors (such as buzz pollination by certain bee groups) and effectiveness for specific crop species that complement the services provided by managed honey bees. The diversity of wild pollinators also provides functional redundancy, ensuring that pollination services persist even when individual species decline due to environmental stressors.

Research increasingly demonstrates that wild pollinators are essential components of sustainable agricultural systems. Garibaldi *et al.* (2013) ^[7] demonstrated that wild pollinators enhance fruit set of crops regardless of honey bee abundance, highlighting their essential role in agricultural pollination systems. The study found that wild pollinator visitation significantly improved fruit set in 41 crop systems worldwide, even in fields with high honey bee densities. This finding suggests that managed honey bees cannot fully substitute for the services provided by diverse wild pollinator communities.

1.5 Research objectives and scope of the review

This comprehensive review article aims to synthesize existing knowledge on the comparative efficiency of managed honey bees and wild pollinators in Central India, with specific objectives including: (1) documenting the diversity and abundance of pollinator communities in Central Indian agroecosystems and identifying knowledge gaps; (2) evaluating the relative pollination efficiency of managed versus wild pollinators for major crop species grown in the region; (3) examining the economic implications of different pollination strategies and the value of pollination services; (4) identifying threats to pollinator populations and their consequences for agricultural productivity and food security; (5) analyzing methodological approaches used in pollination research and their limitations; and (6) proposing research priorities and management recommendations for sustainable pollination services in Central India.

The scope of this review encompasses peer-reviewed research articles, institutional reports, government publications and thesis works relevant to pollination ecology in Central India and comparable agroecological zones of the country. Priority has been given to studies published within the last decade (2015-2025) that employ rigorous experimental or observational methodologies. However, older foundational studies have been included where they provide essential background or represent the only available data for specific topics. The review focuses primarily on insect pollinators, particularly bees, while acknowledging the contributions of other pollinator groups.

2. Literature review

2.1 Global perspectives on pollination ecology and Ecosystem Services

The scientific understanding of pollination ecology has advanced substantially over the past two decades, driven by growing recognition of pollinator decline and its implications for food security and ecosystem functioning. Klein *et al.* (2007) ^[10] conducted a comprehensive global assessment of crop pollination requirements, classifying 87 leading crops according to their dependence on animal pollination. Their analysis revealed that approximately 70% of these crops demonstrated some degree of pollinator dependence, with fruits, vegetables and nuts showing the highest reliance on animal-mediated pollen transfer. This foundational work established the quantitative framework for assessing pollination deficits and valuing pollination services at global and regional scales. The concept of pollination efficiency has been central to comparative studies of different pollinator groups. Ne'eman *et al.* (2010) ^[17] defined pollination efficiency as a composite measure incorporating visit frequency, pollen deposition per visit and subsequent fruit or seed set. This framework has been applied in numerous studies comparing managed honey bees with wild pollinators, enabling standardized comparisons across different crop systems and geographical regions. The efficiency concept recognizes that different pollinators may excel in different components of the pollination process, with some species making frequent visits but depositing little pollen per visit, while others make fewer visits but transfer pollen more effectively.

A landmark meta-analysis by Garibaldi *et al.* (2013) ^[7] analyzing data from 41 crop systems worldwide found that wild pollinators were generally more effective than honey bees on a per-visit basis, though honey bees often compensated through higher visit frequencies. The study concluded that conserving wild pollinator diversity is essential for maintaining stable pollination services and that reliance solely on managed honey bees may leave agricultural systems vulnerable to pollination deficits. This finding has significant implications for pollination management strategies, suggesting that optimal approaches should support both managed colonies and wild pollinator populations.

2.2 Pollination studies in indian agriculture: historical development

Research on crop pollination in India has a rich history dating back to the pioneering work of Shivaram and colleagues at the Central Bee Research and Training Institute (CBRTI) in Pune during the 1960s and 1970s. Early studies documented the role of honey bees in enhancing yields of oilseeds, particularly mustard (*Brassica juncea*) and sunflower (*Helianthus annuus*), establishing the empirical basis for promoting managed pollination services in Indian agriculture (Suryanarayana, 1987) ^[24]. These foundational studies demonstrated yield increases of 20-30% for various crops following honey bee pollination, providing compelling evidence for the economic value of pollination services. Abrol (2007, 2012) ^[1, 2] provided comprehensive reviews of honey bee pollination research in India, synthesizing decades of research findings and establishing protocols for managed pollination services. His work documented the effectiveness of both *Apis mellifera* and *Apis cerana* for various crops, while also highlighting

the importance of wild pollinators that had received less research attention. The reviews identified oilseeds, cucurbits and fruit crops as the categories most responsive to managed pollination, providing guidance for farmers and beekeepers seeking to optimize pollination services.

More recent research has expanded beyond honey bees to encompass the broader pollinator community, reflecting growing global recognition of wild pollinator importance. Studies by Belavadi and Ganeshaiah (2013) [3] in Karnataka documented the diversity of non-*Apis* pollinators in cucurbit crops, identifying stingless bees, solitary bees and butterflies as significant contributors to pollination. Their work highlighted the importance of maintaining habitat diversity to support wild pollinator populations and demonstrated that crop pollination depends on diverse pollinator assemblages rather than single species.

2.3 Managed honey bee species: comparative biology and performance

The two primary managed honey bee species in India, *Apis mellifera* and *Apis cerana indica*, exhibit distinct biological characteristics that influence their suitability for different pollination contexts. *Apis mellifera*, introduced from Europe during the 1960s, has been extensively studied globally, facilitating technology transfer and problem-solving for beekeepers. The species demonstrates higher colony populations (averaging 30,000-60,000 workers in established colonies), greater honey yields (25 kg per colony annually under favorable conditions) and more manageable behavior regarding swarming and absconding (Dalio, 2015) [5]. However, *A. mellifera* is more susceptible to certain pests and diseases, particularly the Varroa destructor mite, which has become a major threat to colonies across India. *Apis cerana indica*, the indigenous cavity-nesting honey bee, has co-evolved with Indian flora over millennia and exhibits several advantageous traits for local pollination services. Research by Pudasaini and Thapa (2014) [20] demonstrated that *A. cerana* visited significantly more rapeseed flowers per minute than *A. mellifera* under both caged and open conditions (24.33 vs. 19.00 flowers/minute in cages; 26.0 vs. 21.67 flowers/minute in open fields). Importantly, *A. cerana* maintained foraging activity under slightly unfavorable conditions (lower temperatures, higher humidity) when *A. mellifera* activity declined, suggesting greater resilience of the native species to variable weather conditions. Studies on cucurbit pollination have consistently shown positive effects of managed *A. cerana* colonies. Research on bitter melon in Tamil Nadu documented yield increases of up to 27.60% with managed *A. cerana* pollination, with optimal results obtained when hives were placed within the cropped area or at 100-meter distances (Yogapriya *et al.* 2025). Similar studies on culinary melon found that *A. cerana indica* ranked highest in pollination efficiency (PE=460,800) based on combined measures of abundance and pollen carriage, significantly outperforming other pollinators including *Ceratina binghami* (PE=38,000) and *Nomia strigata* (PE=81,000) (Vismaya *et al.* 2025) [26].

2.4 Stingless bees: biology, management and pollination efficiency

Stingless bees (*Meliponini*) represent one of the most important groups of wild pollinators in tropical and subtropical regions of India. *Tetragonula iridipennis* (formerly *Trigona iridipennis*), the most widely distributed

stingless bee species in India, has been extensively studied for its pollination potential and management possibilities. Unlike honey bees, stingless bees cannot be easily managed in conventional hives, though recent advances in meliponiculture have developed specialized hive designs for certain species. Their small size, floral fidelity and tolerance of high temperatures make them particularly valuable for pollinating crops with small flowers or those grown under protected conditions.

Research by Layek and Karmakar (2018) [13] documented the nesting characteristics, floral resources and foraging activity of *T. iridipennis* in West Bengal, finding that the species exhibits high floral fidelity and forages within a limited range of 50-100 meters from the nest. This limited foraging range makes stingless bees particularly effective for crops grown in greenhouses or polyhouses, where they remain within the enclosed area unlike honey bees that may escape through vents. Studies on gherkin pollination demonstrated that *T. iridipennis* spent more time on female flowers (26.99 seconds per flower) compared to male flowers (8.81 seconds), indicating efficient pollen transfer behavior (Rakshitha *et al.* 2026) [21].

Research on onion seed production demonstrated that stingless bee pollination improved seed yields by 37.5% in Rabi season and 36% in Kharif season compared to fields without bees (Horizon Publishing, 2025). Seed germination rates were also higher (88% vs. 77% in Rabi; 86% vs. 74% in Kharif) with stingless bee pollination. Studies on coriander seed production found that incorporating stingless bees resulted in a 31% increase in seed production compared to fields without bee colonies, along with honey production of 130g per 10 colonies over 28 days (Saai Vignesh *et al.* 2024) [22].

2.5 Solitary bees: diversity and specialized pollination services

Solitary bees, which constitute the vast majority of bee species diversity, play important but often underappreciated roles in agricultural pollination. Unlike social bees that live in colonies, solitary bees nest individually in soil, wood, or plant stems, with each female constructing and provisioning her own nest. In India, solitary bee diversity includes carpenter bees (*Xylocopa* spp.), leafcutter bees (*Megachile* spp.), blue-banded bees (*Amegilla* spp.), halictid bees and numerous other families, each with distinct ecological requirements and foraging specializations.

Carpenter bees (*Xylocopa* spp.) are large, robust bees capable of buzz pollination, a behavior that enhances pollen release from certain flower types through vibration. Research on *Xylocopa fenestrata* in Eastern Rajasthan documented their foraging activity on major crops, finding that these bees preferentially visited larger, colorful flowers and exhibited peak foraging activity during midday hours (Academia, 2025). Their size and strength enable them to access floral resources that smaller bees cannot exploit, making them important contributors to pollination networks for crops with larger flowers. Blue-banded bees (*Amegilla* spp.) represent another significant group of solitary pollinators in India. These bees are efficient pollinators of various horticultural crops and have been documented as important visitors to bitter melon, tomato and other vegetable crops (Yogapriya *et al.* 2025) [28]. Their distinctive blue abdominal bands and rapid flight patterns make them easily recognizable in agricultural landscapes. Research

suggests that *Amegilla* species may be particularly effective for crops requiring buzz pollination, such as certain solanaceous crops.

2.6 Economic valuation of pollination services in India

The economic valuation of pollination services in India has received systematic attention through the work of researchers who estimated that animal pollination contributes approximately Rs. 112,615 crore (8.72%) annually to Indian agriculture (Singh *et al.* 2017) ^[23]. This valuation, based on crop-specific dependence ratios and production values, provided the first comprehensive assessment of pollinator contributions to the national agricultural economy. The study identified oilseeds, fruits and vegetables as the crop categories most dependent on pollinator services, with mustard alone benefiting by approximately Rs. 19,355 crore annually from animal pollination. According to the Ministry of Statistics & Programme Implementation (2026) ^[15], the monetary value of pollination services has increased substantially, reaching Rs. 266.33 thousand crore in 2021-22, representing approximately 8-10% of total crop output value. This increase reflects both growth in agricultural production and improved understanding of pollination dependence for various crops. The analysis found that fruits and vegetables contributed the largest share to total pollination value, reflecting their high dependence on pollination services and significant market value. Oilseeds (about 27-32%) and fibers (about 22-23%) consistently showed the highest dependence ratios. Economic analyses of specific crop systems have demonstrated substantial returns from pollination investments. Research in Kashmir valley estimated the potential value of managed pollination services for apple at INR 126.56 billion per annum, with additional welfare implications of INR 29.71 billion if managed pollination were extended to all apple-growing areas (Mahendar *et al.* 2017) ^[14]. Studies on pomegranate production under the 'Madhu Sandesh' project found that farmers who rented beehives saw yield increases of 35% and net income increases of 42%, demonstrating the tangible economic benefits of managed pollination.

2.7 Threats to pollinator populations: a multi-factorial challenge

Pollinator populations worldwide face multiple, interacting threats that have contributed to documented declines in both abundance and diversity. Habitat loss and fragmentation resulting from agricultural intensification, urbanization and deforestation represent primary drivers of pollinator decline (Potts *et al.* 2010) ^[19]. In India, the conversion of diverse agricultural landscapes to intensive monoculture systems has reduced the availability of floral resources and nesting sites for wild pollinators. The expansion of commercial agriculture has been accompanied by increased pesticide use, with neonicotinoid insecticides particularly implicated in pollinator toxicity (Imran *et al.* 2024) ^[8]. Pesticide exposure represents a critical threat to pollinator health and survival. Neonicotinoid insecticides, which constitute approximately 40% of the global pesticide market, are systemic compounds that persist in plant tissues and can be expressed in pollen and nectar. Research has documented sublethal effects on bee behavior, navigation, learning and reproductive success even at low exposure levels. Studies in India have detected pesticide residues in honey bee colonies

and wild bee populations, raising concerns about chronic exposure effects. The indiscriminate use of pesticides, often without adherence to label recommendations regarding application timing relative to flowering, exacerbates these risks.

Climate change poses emerging threats to pollinator communities through multiple pathways. Phenological mismatches between flowering plants and their pollinators can disrupt established relationships, reducing reproductive success for both partners. Research in the Western Ghats documented shifts in flowering phenology of *Terminalia paniculata*, with potential consequences for pollinator interactions (Wiley, 2025). Extreme weather events, including heat waves, droughts and unseasonal rainfall, can directly impact pollinator survival and foraging activity. Changes in temperature and precipitation patterns can also affect the distribution and abundance of floral resources, altering the carrying capacity of landscapes for pollinator populations. Diseases and parasites represent significant threats to managed honey bee colonies and potentially to wild populations. The *Varroa destructor* mite, originally a parasite of *Apis cerana*, has successfully colonized *A. mellifera* populations and spread globally. In India, *Varroa* was first reported in *A. mellifera* colonies in 1988 and has since become established throughout the country (Kumar *et al.* 2008) ^[12]. The mite feeds on honey bee hemolymph, transmitting viruses and weakening colonies. Other diseases including Thai sac brood virus, which devastated *A. cerana* populations in southern India during the 1990s, continue to impact managed beekeeping operations. The potential for disease transmission from managed to wild bee populations Remains a concern.

2.8 Conservation strategies and policy frameworks

Conservation of pollinator populations requires integrated approaches addressing multiple threats simultaneously. Habitat conservation and restoration represent foundational strategies, involving the protection of natural habitats, creation of pollinator-friendly habitats within agricultural landscapes and maintenance of hedgerows, field margins and non-crop flowering plants. The establishment of wildflower strips, beetle banks and conservation headlands within agricultural fields can provide floral resources and nesting sites for wild pollinators throughout the growing season. Agroforestry systems that integrate flowering trees and shrubs with crops offer particular promise for supporting pollinator populations while providing additional benefits to farmers. Pesticide risk mitigation strategies include the development and adoption of pollinator-friendly pest management approaches, such as Integrated Pest and Pollinator Management (IPPM), which explicitly considers pollinator conservation alongside pest control objectives. Selective pesticide use, avoiding applications during flowering periods and choosing products with lower toxicity to pollinators can reduce pesticide impacts while maintaining crop protection. The promotion of biological control and other non-chemical pest management methods can further reduce reliance on pesticides. Policy frameworks supporting pollinator conservation have emerged at international, national and regional levels. The Convention on Biological Diversity has recognized pollinator conservation as a priority and the International Pollinator Initiative provides a framework for coordinated action. In India, the National Beekeeping and Honey Mission

(NBHM) launched in 2020 represents a significant policy commitment to apiculture development, though its focus on honey production could be balanced with greater emphasis on pollination services and wild pollinator conservation. State-level initiatives and integration of pollinator considerations into broader agricultural and environmental policies would strengthen the policy framework for pollinator conservation.

3. Methodology

3.1 Literature search strategy and databases

This review employed a systematic and comprehensive approach to identify, evaluate and synthesize relevant literature on pollination ecology and pollinator efficiency in Central India and comparable agroecological zones. Literature searches were conducted across multiple academic databases including Google Scholar, ResearchGate, Academia.edu, PubMed, Web of Science and institutional repositories of Indian agricultural universities and research institutions. The search strategy employed combinations of keywords and phrases including 'pollination ecology India', 'honey bee pollination efficiency', 'wild pollinators agriculture', 'Apis mellifera Apis cerana comparison', 'stingless bees pollination', 'Tetragonula iridipennis', 'crop yield pollinators', 'Central India pollination', 'Madhya Pradesh bee diversity', 'pollinator conservation India', 'economic value pollination services' and 'Integrated Pest Pollinator Management'.

Priority was given to peer-reviewed journal articles published in reputable scientific journals, government publications from ministries and departments, institutional reports from agricultural research organizations and doctoral dissertations and master's theses from recognized universities. The review focused primarily on literature published within the last decade (2015-2025) to ensure currency of information, though older foundational studies were included where they provided essential background or represented the only available data for specific topics. Citations were managed and organized using systematic approaches to ensure comprehensive coverage and prevent omission of relevant studies.

3.2 Inclusion and exclusion criteria

Studies were included in this review if they met the following predetermined criteria: (1) conducted in India or comparable tropical/subtropical agroecosystems with relevance to Indian conditions; (2) provided quantitative data on pollinator diversity, abundance, or efficiency; (3) assessed impacts of pollination on crop yield, quality, or economic value; (4) compared multiple pollinator species or groups; (5) employed rigorous experimental or observational methodologies with clear descriptions of sampling protocols and statistical analyses; and (6) were published in English or had detailed English abstracts available.

Studies were excluded if they: (1) lacked clear methodological descriptions that would enable assessment of result reliability; (2) did not provide quantitative results or presented only anecdotal observations; (3) focused exclusively on non-agricultural ecosystems without clear relevance to crop pollination; (4) were published in non-peer-reviewed sources without adequate quality verification; (5) were review articles or meta-analyses that did not present original data (though these were consulted for

background and cross-referencing); or (6) were duplicate publications or conference abstracts without full paper availability.

3.3 Analytical framework and synthesis approach

The synthesis of literature followed a thematic approach organized around key topics including pollinator diversity and community composition, comparative efficiency of managed versus wild pollinators, economic valuation of pollination services, threats to pollinator populations and management strategies for sustainable pollination. Quantitative data on pollination efficiency, expressed as percentage yield increases, pollen deposition rates, fruit set improvements, or economic value, were compiled and compared across studies. Where possible, effect sizes were calculated to standardize comparisons across different crops and pollinator species. The review also critically evaluated methodological approaches used in different studies, identifying strengths and limitations that inform the reliability of conclusions. Particular attention was paid to sampling design, replication, statistical analysis and potential sources of bias. This critical evaluation enabled assessment of the weight of evidence for different conclusions and identification of areas where additional research with improved methodologies is needed. The synthesis aimed to identify consistent patterns across studies while acknowledging contextual factors that may explain variation in results.

3.4 Quality assessment and limitations

The quality of included studies was assessed based on criteria including sampling adequacy, methodological rigor, statistical appropriateness and clarity of reporting. Studies meeting higher quality standards were given greater weight in the synthesis, though all relevant studies meeting inclusion criteria were considered. Limitations of this review include the geographic bias in available research, with most studies conducted in southern, northern, or western India and limited research specifically from Central India. This necessitates extrapolation from other regions, which may not fully capture the specific conditions of Central Indian agroecosystems. Additional limitations include the heterogeneity of methodologies employed across studies, which complicates quantitative synthesis and meta-analysis. Variation in sampling protocols, efficiency metrics, crop varieties and environmental conditions introduces noise that may obscure true patterns. Publication bias toward positive results may also affect the literature, with studies finding significant pollination effects more likely to be published than those finding no effect. Despite these limitations, the review provides the most comprehensive synthesis currently possible of pollination ecology research relevant to Central India.

4. Results and Thematic Analysis

4.1 Pollinator diversity in Indian agroecosystems

The available literature documents substantial pollinator diversity across Indian agricultural landscapes, though specific studies from Central India remain limited compared to other regions. Research in neighboring agroecological zones provides insights into the pollinator communities likely present in Central India. Studies in Tamil Nadu documented 12-16 pollinator species visiting bitter melon crops, including *Apis cerana indica*, *Apis florea*,

Tetragonula iridipennis, *Amegilla zonata*, various halictid bees and butterflies (Yogapriya *et al.* 2025) ^[28]. Similar diversity was reported for mustard crops in the Himalayan region, where 15 pollinator species were recorded, with *A. cerana* being the most abundant visitor (Chauhan *et al.* 2024) ^[4]. The composition of pollinator communities varies significantly with crop type, flowering phenology and landscape context. Sunflower crops in Maharashtra attracted predominantly honey bees (*Apis* spp. constituting 88.85% of visitors), with *A. mellifera* being the most efficient pollinator for hybrid seed production (Krishna *et al.* 2014) ^[11]. In contrast, cucurbit crops supported more diverse pollinator assemblages including stingless bees, solitary bees and butterflies. This variation highlights the importance of maintaining diverse pollinator communities to ensure pollination services across different crop types with varying floral morphologies and blooming periods.

Research in the Western Ghats documented 27 species of stingless bees across India, with *Tetragonula iridipennis* being the most widely distributed and well-studied species for crop pollination (Nature, 2024). The study found that stingless bee distribution is influenced by climatic factors including temperature and precipitation, with potential range shifts expected under climate change scenarios. Understanding these distribution patterns is essential for predicting where specific pollinator species may be available for managed pollination services.

4.2 Comparative pollination efficiency: managed honey bees

Comparative studies between *Apis mellifera* and *Apis cerana* have yielded nuanced results depending on crop species, environmental conditions and management practices. Research on sunflower pollination in Maharashtra found that six-framed *A. mellifera* colonies produced the highest seed yields (16.4 q/ha), representing a 21% increase over open pollination and 48% increase over pollinator-excluded controls (Krishna *et al.* 2014) ^[11]. The study also documented improved seed quality parameters including lower percentages of crinkled seeds (8.2% vs. 24% in open pollination) and higher germination rates (94.3% vs. 89% in open pollination).

However, studies under suboptimal conditions have demonstrated advantages for *A. cerana*. Research in Nepal found that *A. cerana* visited significantly more rapeseed flowers per minute than *A. mellifera* under both caged and open conditions (24.33 vs. 19.00 flowers/minute in cages; 26.0 vs. 21.67 flowers/minute in open fields) (Pudasaini & Thapa, 2014) ^[20]. Importantly, *A. cerana* maintained foraging activity under slightly unfavorable conditions (lower temperatures, higher humidity) when *A. mellifera* activity declined, suggesting greater resilience of the native species to variable weather conditions that are common in rainfed agricultural systems. Studies on cucurbit pollination have consistently shown positive effects of managed *A. cerana* colonies. Research on bitter melon in Tamil Nadu documented yield increases of up to 27.60% with managed *A. cerana* pollination, with optimal results obtained when hives were placed within the cropped area or at 100-meter distances (Yogapriya *et al.* 2025) ^[28]. Honey yield from these colonies provided additional income for farmers, enhancing the economic viability of using managed bees for pollination. Similar studies on culinary melon found that *A. cerana indica* ranked highest in pollination efficiency

(PE=460,800) based on combined measures of abundance and pollen carriage, significantly outperforming other pollinators (Vismaya *et al.* 2025) ^[26].

4.3 Pollination efficiency of wild pollinators

Wild pollinators demonstrate significant pollination efficiency across diverse crop systems, often exceeding that of managed honey bees on a per-visit basis. Stingless bees (*Tetragonula iridipennis*) have emerged as particularly effective pollinators for vegetable crops, especially those grown under protected conditions. Studies on gherkin under polyhouse conditions found that *T. iridipennis* exhibited peak activity between 11:00-12:00 hours, coinciding with flower opening and spent more time on female flowers (26.99 seconds) compared to male flowers (8.81 seconds), indicating efficient pollen transfer behavior (Rakshitha *et al.* 2026) ^[21]. Managed stingless bee pollination increased gherkin yields by 97.65% compared to controls.

Research on onion seed production demonstrated that stingless bee pollination improved seed yields by 37.5% in Rabi season and 36% in Kharif season compared to fields without bees (Horizon Publishing, 2025). Seed germination rates were also higher (88% vs. 77% in Rabi; 86% vs. 74% in Kharif) with stingless bee pollination, indicating improved seed quality. These findings highlight the potential for integrating stingless bees into managed pollination systems, particularly for crops grown under protected conditions where honey bees may be less effective or may escape from the enclosure. Carpenter bees (*Xylocopa* spp.) and blue-banded bees (*Amegilla* spp.) contribute significantly to pollination of crops requiring buzz pollination or those with larger floral structures. Research at Tamil Nadu Agricultural University documented eight non-*Apis* bee species across horticultural crops, with carpenter bees and blue-banded bees being important visitors to crops with larger flowers (Academia, 2025). These solitary bees often exhibit high floral constancy, potentially increasing the efficiency of pollen transfer between conspecific plants. Their effectiveness for specific crops, particularly those in the Solanaceae family, warrants further investigation.

4.4 Economic implications and value of pollination services

The economic valuation of pollination services in India underscores the substantial contribution of pollinators to agricultural productivity and national food security. According to the Ministry of Statistics & Programme Implementation (2026) ^[15], the monetary value of pollination services increased from Rs. 115.41 thousand crore in 2012-13 to Rs. 266.33 thousand crore in 2021-22, representing approximately 8-10% of total crop output value. This growth reflects both increases in agricultural production and improved understanding of pollination dependence for various crops. The analysis found that fruits and vegetables contributed the largest share to total pollination value, reflecting their high dependence on pollination services and significant market value. Crop-specific analyses reveal substantial variation in pollination dependence and economic value. Oilseeds, particularly mustard and sunflower, show the highest dependence on pollinators (dependence ratio=0.65), with mustard alone benefiting by approximately Rs. 19,355 crore annually from animal pollination (Singh *et al.* 2017) ^[23]. Sunflower

benefits by approximately Rs. 1,153 crore annually from pollinator services. Fruits including apple (Rs. 3,625 crore), cashew (Rs. 3,484 crore), citrus (Rs. 2,333 crore) and guava (Rs. 1,858 crore) derive significant economic value from pollination services. These valuations provide compelling economic rationale for investments in pollinator conservation and managed pollination.

Economic analyses of specific crop systems have demonstrated substantial returns from pollination investments. Research in Kashmir valley estimated the potential value of managed pollination services for apple at INR 126.56 billion per annum, with additional welfare implications of INR 29.71 billion if managed pollination were extended to all apple-growing areas (Mahendar *et al.* 2017) [14]. The 'Madhu Sandesh' pilot project in Maharashtra demonstrated that pomegranate farmers who rented beehives saw yield increases of 35% and net income increases of 42%, while onion seed producers saw yield increases of 17% and income increases of 18%. These case studies demonstrate the tangible economic benefits of managed pollination services.

4.5 Threats to pollinator populations and conservation status

Multiple threats confront pollinator populations across Indian agricultural landscapes, with implications for the sustainability of pollination services. Pesticide exposure represents a primary concern, with neonicotinoid insecticides particularly implicated in pollinator toxicity. These systemic insecticides, which constitute approximately 40% of the global pesticide market, persist in soil and water and affect non-target organisms including pollinators (Imran *et al.* 2024) [8]. Research has documented sublethal effects on bee behavior, navigation, learning and reproductive success even at low exposure levels. Studies in India have detected pesticide residues in honey bee colonies and wild bee populations, raising concerns about chronic exposure effects.

Habitat loss and fragmentation resulting from agricultural intensification have reduced the availability of floral resources and nesting sites for wild pollinators. The conversion of diverse agricultural landscapes to intensive monoculture systems eliminates the non-crop flowering plants that sustain pollinator populations between crop flowering periods. Studies in various regions of India have documented declines in pollinator diversity associated with agricultural intensification, with forest-agriculture mosaics supporting higher pollinator diversity than intensive agricultural areas. The loss of traditional agroforestry systems and hedgerows has further reduced habitat availability. Climate change poses emerging threats through phenological mismatches and extreme weather events. Research in the Western Ghats documented shifts in flowering phenology of forest tree species, with potential consequences for pollinator interactions (Wiley, 2025). Such mismatches can disrupt established plant-pollinator relationships, reducing reproductive success for both partners. Extreme temperatures and unpredictable rainfall patterns can directly impact pollinator survival and foraging activity. Changes in temperature and precipitation patterns can also affect the distribution and abundance of floral resources, altering the carrying capacity of landscapes for pollinator populations. Diseases and parasites represent significant threats to managed honey bee colonies. The

Varroa destructor mite, originally a parasite of *Apis cerana*, has successfully colonized *A. mellifera* populations and spread throughout India since its first detection in 1988 (Kumar *et al.* 2008) [12]. The mite feeds on honey bee hemolymph, transmitting viruses and weakening colonies. Thai sac brood virus devastated *A. cerana* populations in southern India during the 1990s, causing colony losses exceeding 90% in affected areas. Other emerging diseases and pests continue to threaten managed beekeeping operations, with implications for pollination service availability.

4.6 Comparative Analysis: Managed vs. Wild Pollinators

A synthesis of available studies enables comparative assessment of managed honey bees versus wild pollinators across multiple dimensions. In terms of pollination efficiency per visit, wild pollinators often demonstrate superiority, with studies showing that stingless bees, solitary bees and native honey bees can deposit more pollen per flower visit than managed *A. mellifera*. However, managed honey bees typically compensate through higher visit frequencies and greater colony densities, resulting in substantial overall pollination contributions. The optimal strategy depends on crop characteristics, with some crops benefiting more from the specialized behaviors of wild pollinators while others respond well to managed honey bee pollination. Economic considerations favor managed honey bees in many contexts due to their manageability, colony strength and additional honey production. However, wild pollinators provide services at no direct cost to farmers and contribute to pollination of crops and wild plants outside of managed systems. The insurance value of wild pollinators, ensuring pollination services when managed colonies fail, represents an important but often unquantified economic benefit. Conservation investments in wild pollinator habitats may provide returns comparable to or exceeding investments in managed pollination, particularly when long-term sustainability is considered. Resilience considerations increasingly favor diversified pollination strategies. Relying solely on managed *A. mellifera* creates vulnerability to disease outbreaks, colony losses and management failures. Maintaining diverse pollinator communities provides functional redundancy that can buffer against environmental variability and species-specific declines. Climate change further strengthens the case for diversification, as different pollinator species may respond differently to changing temperature and precipitation patterns.

5. Discussion

5.1 Synthesis of comparative efficiency findings

The synthesis of available literature reveals a complex picture of pollinator efficiency that defies simple generalizations about the superiority of managed versus wild pollinators. Rather, the evidence suggests that different pollinator groups exhibit complementary strengths that vary with crop species, environmental conditions and landscape context. Managed honey bees, particularly *Apis mellifera*, offer advantages in terms of colony strength, manageability and consistent performance under favorable conditions. Their large colony populations enable them to provide substantial pollination services over extensive areas, making them economically attractive for commercial pollination operations. The higher honey yields from *A. mellifera* colonies also provide additional income streams that can

offset management costs. However, wild pollinators demonstrate several advantages that warrant their conservation and integration into pollination management strategies. First, wild pollinators often exhibit higher per-visit efficiency for specific crop species. The documented superiority of *A. cerana* in flower visitation rates under suboptimal conditions, the effectiveness of stingless bees for greenhouse crops and the specialized behaviors of solitary bees for buzz-pollinated crops all highlight the functional complementarity of wild pollinators. Second, wild pollinators provide insurance against pollination deficits that can occur when managed colonies underperform due to disease, weather, or management issues. This insurance function is particularly valuable given the increasing variability of weather conditions associated with climate change. The concept of 'functional complementarity' emerges as a key insight from this review. Rather than viewing managed and wild pollinators as competitors or substitutes, the evidence supports conceptualizing them as complementary components of diverse pollination networks. This perspective aligns with the findings of Garibaldi *et al.* (2013) [7], who demonstrated that wild pollinators enhance fruit set regardless of honey bee abundance. The practical implication is that optimal pollination management should aim to support both managed colonies and wild pollinator populations, rather than focusing exclusively on one or the other. This integrated approach can provide more stable and resilient pollination services across varying environmental conditions.

5.2 Critical evaluation of research methodologies

The methodologies employed in pollination efficiency studies exhibit significant variation that affects the comparability of results. Pollination efficiency has been measured using diverse metrics including visit frequency, pollen deposition per visit, fruit set percentage, seed yield, seed quality parameters and economic value. While each metric captures important aspects of pollination service, the lack of standardization complicates cross-study comparisons. Future research should adopt standardized protocols for assessing pollination efficiency, ideally incorporating multiple metrics that capture both quantity and quality dimensions of pollination service.

Experimental designs have varied from cage studies that exclude non-target pollinators to open-field observations that capture natural pollination dynamics. Cage studies offer greater control and enable attribution of effects to specific pollinator species, but may not reflect real-world conditions where multiple pollinator species interact. Open-field studies capture natural dynamics but make it difficult to isolate the contributions of specific pollinators. Both approaches have value and comprehensive assessments should ideally incorporate multiple methodological approaches. The development of molecular techniques such as pollen DNA metabarcoding offers new opportunities for characterizing pollinator foraging patterns with greater precision. Sampling protocols for pollinator community assessment also vary across studies, with implications for comparability. Methods including visual observation, sweep netting, pan trapping and transect walks have been employed, each with distinct biases and limitations. Visual observation enables behavioral studies but may miss cryptic or fast-moving species. Sweep netting provides specimens for identification but may disturb pollinators and affect their

behavior. Pan trapping can sample over extended periods but may have selectivity for certain species. Standardization of sampling protocols would enable more robust comparisons across studies and regions.

5.3 Research gaps and limitations

Several significant research gaps emerge from this review. First, there is a paucity of systematic research specifically from Central India, with most studies conducted in southern, northern, or western regions of the country. The agroecological conditions of Central India, characterized by distinct climatic patterns, soil types, cropping systems and landscape contexts, warrant targeted research to inform region-specific pollination management recommendations. The extrapolation of findings from other regions may not fully capture the specific conditions and challenges of Central Indian agriculture. Second, long-term monitoring data on pollinator community dynamics are largely absent, limiting our understanding of population trends, seasonal variations and responses to environmental changes. Most studies represent single-season or short-term observations that cannot capture interannual variability or long-term trends. Establishment of long-term monitoring sites in Central India would provide valuable baseline data and enable detection of changes over time. Such monitoring should employ standardized protocols to enable spatial and temporal comparisons. Third, the interactive effects of multiple pollinator species on crop pollination remain poorly understood. Most studies have focused on single pollinator species or compared pairs of species, while natural pollination typically involves diverse assemblages of pollinators. The potential for synergistic or antagonistic interactions between managed and wild pollinators warrants investigation. Experimental manipulations of pollinator community composition, combined with measurements of crop reproductive success, could reveal whether synergistic effects occur when multiple pollinator species are present. Fourth, the economic analysis of pollination services has focused primarily on direct yield impacts, while broader ecosystem service values and the economic benefits of pollinator-friendly agricultural practices remain underexplored. Cost-benefit analyses comparing different pollination management strategies, including the costs of habitat creation and maintenance, would inform farmer decision-making and policy development. The economic valuation of wild pollinator contributions specifically deserves greater attention.

5.4 Implications for agricultural policy and practice

The findings of this review carry significant implications for agricultural policy and practice in Central India. The substantial economic value of pollination services provides a strong rationale for policy interventions that support pollinator conservation and managed pollination. The National Beekeeping and Honey Mission (NBHM), launched in 2020 with an outlay of Rs. 500 crore, represents a positive step toward promoting scientific beekeeping and pollination services. However, the mission's focus on honey production should be balanced with greater emphasis on pollination services and wild pollinator conservation. Integration of pollination considerations into broader agricultural policies and programs would enhance sustainability. The concept of Integrated Pest and Pollinator Management (IPPM) offers a promising framework for

reconciling pest management needs with pollinator conservation. By integrating pollinator considerations into IPM programs, farmers can reduce pesticide use during flowering periods, adopt selective pesticides with lower toxicity to pollinators and maintain non-crop floral resources that support wild pollinator populations. The 'Madhu Sandesh' pilot project in Maharashtra demonstrated the feasibility and benefits of this integrated approach, with participating farmers achieving yield increases of 35% for pomegranate and 17% for onion seed while reducing pesticide use. Scaling up such initiatives could have significant impacts on agricultural sustainability.

Agroforestry systems offer particular promise for supporting pollinator populations while providing additional benefits for farmers. The integration of flowering trees and shrubs into agricultural landscapes can provide continuous floral resources for pollinators throughout the year, maintain habitat diversity and generate additional income through timber, fruit, or fodder production. Research has documented higher pollinator diversity in agroforestry systems compared to intensive monocultures, suggesting that agroforestry promotion should be a component of pollinator conservation strategies. Policy support for agroforestry adoption could simultaneously address multiple objectives including pollinator conservation, climate resilience and farmer livelihoods. Extension and capacity building are essential for translating research findings into practice. Farmers need information about the benefits of pollinators, techniques for supporting wild pollinator populations and options for accessing managed pollination services. Beekeepers require training in colony management for pollination, including timing of colony placement, colony strength requirements and strategies for maximizing pollination effectiveness. The development of pollination service markets, including hive rental systems and quality standards, could facilitate farmer access to managed pollination.

6. Future research directions

6.1 Priority research areas for central India

Based on the gaps identified in this review, several priority research areas emerge for advancing pollination ecology in Central India. First, systematic baseline surveys of pollinator communities across different agroecological zones of Central India are essential for documenting species diversity, abundance patterns and seasonal dynamics. Such surveys should employ standardized sampling protocols including visual observations, sweep netting and pan trapping to enable spatial and temporal comparisons. The establishment of long-term monitoring sites would provide valuable data on population trends and responses to environmental changes, including climate variability and land use change.

Second, comparative efficiency studies specifically focused on major crops of Central India (mustard, sunflower, gram, lentil, soybean, cotton, vegetables) would provide region-specific guidance for pollination management. These studies should employ standardized methodologies that enable comparison across pollinator species and crop types and should assess both quantity (yield) and quality (seed viability, fruit characteristics, nutritional content) dimensions of pollination service. Particular attention should be paid to crops showing high pollination dependence but limited research attention. Third, research

on the interactive effects of managed and wild pollinators would inform integrated pollination management strategies. Experimental manipulations of pollinator community composition, combined with measurements of crop reproductive success, could reveal whether synergistic effects occur when multiple pollinator species are present. Such information would support decisions about whether to invest solely in managed colonies or to also implement wild pollinator conservation measures. Network approaches that examine plant-pollinator interactions at the community level could reveal important functional relationships.

6.2 Methodological innovations and technology applications

Advances in methodology offer opportunities for more comprehensive assessment of pollination dynamics. Molecular techniques including pollen DNA metabarcoding enable detailed characterization of pollinator foraging patterns and floral resource use without requiring direct observation. Recent research applying honey DNA metabarcoding to compare foraging signatures of *Apis florea* and *A. cerana* demonstrated the potential of this approach for understanding resource partitioning between pollinator species (Nature, 2025). Application of such techniques in Central India could reveal how different pollinator species utilize available floral resources across seasons and landscapes. Remote sensing and GIS approaches can contribute to landscape-scale analyses of pollinator habitat availability and connectivity. Mapping floral resource availability across agricultural landscapes would enable identification of pollinator 'deserts' and prioritization of areas for habitat restoration. Coupling such maps with pollinator community data could reveal landscape factors that influence pollinator diversity and abundance. The integration of citizen science data through platforms such as SeasonWatch could expand monitoring capacity and engage farming communities in pollinator conservation. Automated monitoring technologies including camera traps, acoustic sensors and computer vision approaches offer potential for continuous pollinator monitoring without requiring constant human presence. While these technologies are still under development, they may eventually enable cost-effective monitoring of pollinator populations at scales not feasible with traditional methods. Investment in adapting these technologies for Indian agricultural contexts could yield significant benefits for pollinator research and monitoring.

6.3 Climate change research and adaptation strategies

Understanding and preparing for climate change impacts on pollination systems represents an urgent research priority. Studies documenting phenological shifts in both crops and their pollinators would enable assessment of mismatch risks. Experimental approaches manipulating temperature and precipitation conditions could reveal pollinator species' vulnerability to climate extremes. Such information would inform the development of climate-resilient pollination management strategies, potentially including the selection of pollinator species better adapted to projected future conditions. Research on the thermal tolerance of different pollinator species could guide management decisions as temperatures rise. Species such as *Apis florea*, which can survive temperatures up to 50°C, may become increasingly important in hotter regions. The potential range shifts of

both crops and their pollinators under climate change scenarios should be modeled to anticipate future mismatches. Adaptation strategies including the selection of heat-tolerant crop varieties and the provision of shade structures for pollinators may become necessary.

6.4 Socioeconomic dimensions and policy research

Research on the socioeconomic dimensions of pollination management would support policy development and extension efforts. Studies examining farmers' knowledge, attitudes and practices regarding pollinators could identify barriers to adoption of pollinator-friendly practices and inform targeted extension interventions. Economic analyses comparing the costs and benefits of different pollination management strategies would enable evidence-based recommendations for farmers with different resource endowments and risk profiles. Policy research should examine the effectiveness of existing programs supporting pollinators and identify opportunities for improvement. The National Beekeeping and Honey Mission represents a significant investment in apiculture, but its impacts on pollination services and wild pollinator conservation deserve evaluation. Research on pollination service markets, including pricing mechanisms, quality standards and contractual arrangements, could inform the development of functional markets that benefit both farmers and beekeepers. Gender dimensions of pollinator management deserve attention, as women often play significant roles in agricultural decision-making but may face barriers to accessing training and resources. Research examining how pollinator management practices affect different household members could ensure that extension approaches are inclusive and equitable. The potential for beekeeping and pollinator-friendly practices to provide income opportunities for women and marginalized groups should be explored.

7. Conclusion

This comprehensive review has examined the comparative efficiency of managed honey bees and wild pollinators in Central India, synthesizing available evidence from diverse agroecological zones of the country. Several key conclusions emerge from this analysis with important implications for research, policy and practice. First, both managed honey bees (*Apis mellifera* and *Apis cerana*) and wild pollinators (stingless bees, solitary bees and other insects) contribute significantly to crop pollination, with their relative efficiency varying by crop species, environmental conditions and management practices. Rather than viewing these pollinator groups as competitors, the evidence supports conceptualizing them as functionally complementary components of diverse pollination networks that together provide resilient pollination services. Second, the economic value of pollination services in India is substantial and growing, estimated at Rs. 266.33 thousand crore annually (2021-22), representing approximately 8-10% of total crop output value. This valuation provides a strong economic rationale for investments in pollinator conservation and managed pollination services. The high dependence of oilseeds, fruits and vegetables on pollinator services means that pollinator declines would have disproportionate impacts on these economically important crop categories. However, realizing these benefits requires addressing the multiple threats facing pollinator populations, including habitat loss, pesticide exposure, climate change

and diseases. Third, significant research gaps remain, particularly regarding region-specific data from Central India and long-term monitoring of pollinator community dynamics. Addressing these gaps through systematic research employing standardized methodologies would enable evidence-based recommendations for pollination management in the region. Priority research areas include baseline surveys of pollinator communities, comparative efficiency studies for major regional crops, investigation of interactive effects between managed and wild pollinators and assessment of climate change impacts on pollination systems. Fourth, the integration of pollinator considerations into agricultural policy and practice represents a critical need. The National Beekeeping and Honey Mission provides a foundation for promoting managed pollination, but greater emphasis on wild pollinator conservation and the adoption of Integrated Pest and Pollinator Management approaches would enhance sustainability. Agroforestry systems, pollinator-friendly farming practices and habitat restoration offer promising pathways for supporting pollinator populations while maintaining agricultural productivity and farmer livelihoods. Finally, ensuring sustainable pollination services for Central Indian agriculture requires a multifaceted approach that combines managed honey bee keeping with wild pollinator conservation, integrated pest management with pollinator protection and agricultural productivity with ecosystem stewardship. The tiny creatures that flit from flower to flower in our agricultural landscapes carry immense importance for food security, rural livelihoods and ecological sustainability. Their conservation and effective management represent investments in our collective future, ensuring that the vital ecosystem service of pollination continues to support Indian agriculture for generations to come.

The path forward requires collaboration among researchers, policymakers, extension workers, farmers and beekeepers to develop and implement sustainable pollination management strategies. By valuing and protecting the diverse pollinators that serve our agricultural systems, we can build resilience into our food production systems while supporting biodiversity conservation and rural livelihoods. The sweet rewards of pollination, harvest after harvest, depend on the choices we make today to protect these essential ecosystem service providers.

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