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Assessment of Insect Pollinator Diversity and Their Role in Enhancing Agricultural Productivity

Dr. Chintalapati Neelima Rani[1], Dr. Shital Deshmukh[2], Dr. Sudhir Kadam[3], Dr. P. Vanishree Sah[4], Dr. Bhawana Bisht[5], Shaik Akbar[6]

[1]Assistant Professor, Department of Management, Vivekananda Global University, Jaipur Rajasthan, chintalapati.neelima@vgu.ac.in, ORCID: 0000-0001-9915-2394
[2]Associate Professor, Department Of Zoology, SSESAmt's Science College, Nagpur Maharashtra, drshitaldeshmukh@gmail.com
[3]Associate Professor, School of Engineering, Ajeenkya D Y Patil University, Pune, India. sudhir.kadam@adypu.edu.in
[4]Associate Professor, Department of Humanities and Sciences, CVR College of Engineering, pvanishree@gmail.com
[5]Professor, Graphic Era Deemed to be University , Dehradun, Uttrakhand, India, bishtbhawana29@gmail.com
[6]Associate Professor, Department Of CSE(AI and ML), Geethanjali college of engineering and technology, Medchal, Hyderabad, Telangana, akbarshaik71185@gmail.com

ABSTRACT: Insect pollination links biodiversity directly to food production, because most major crops produce more, or better, fruit and seed when visited by animals. Whether it is the abundance of a few managed species or the diversity of the wider pollinator community that sustains yields, and how much of either is being lost, are open questions for agronomists and policymakers. This paper reviews the empirical evidence on how insect pollinator diversity is measured, how it relates to crop yield and quality, and which pressures threaten it. It combines diversity-measurement theory with crop-level field studies, landscape studies, meta-analyses, and global assessments. Four findings emerge. First, dependence is large: 87 of the 115 leading global food crops benefit from animal pollination, accounting for about 35 percent of global crop production volume, and the annual market value attributable to pollinators is estimated at $235 to $577 billion. Second, wild insects are not substitutes for honey bees but complements: across 41 crop systems, wild insects enhanced fruit set about twice as much as honey bees per visit, and honey bee visits did not replace them. Third, the diversity argument is real but more nuanced than often stated: a few common species deliver most crop visits at a single site, yet different species matter across places and years. Fourth, pressures are severe and interacting. Flying insect biomass fell 76 percent over 27 years in German protected areas, while the global trend in terrestrial insect abundance is about 9 percent per decade. Managed honey bee stocks grew 45 percent over decades in which pollinator-dependent crops expanded about 300 percent. Two comparative tables map the evidence on diversity and yield, and map threats to mitigations. The paper then proposes a farm-level assessment protocol that links diversity metrics to pollination deficit and economic value. The protocol is a conceptual synthesis of the reviewed literature and has not been tested.

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I. INTRODUCTION

Animal pollination affects most of the crops people eat. Klein and coauthors examined the 115 leading global food crops and found that 87 benefit from animal pollination to some degree, and that these crops account for about 35 percent of global production volume, although the crops that depend least on pollinators, mainly cereals, supply most of the calories [1]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) assessment estimated that the annual global market value of output directly attributable to pollinators was $235 billion to $577 billion, and that 5 to 8 percent of current global agricultural production by volume would be lost without them [2]. Gallai, Salles, Settele, and Vaissière valued the contribution at €153 billion in 2005, equal to 9.5 percent of the value of world agricultural food production [3]. That share implies a total world food-production value of about €1.6 trillion (a derived figure, 153 divided by 0.095).

These values depend on insect populations that are under pressure. Hallmann and coauthors used standardized traps at 63 protected sites in Germany and reported that flying insect biomass declined by 76 percent over 27 years, and by 82 percent in midsummer [4]. Sánchez-Bayo and Wyckhuys reviewed insect-decline studies and concluded that about 40 percent of insect species were in decline, with agricultural intensification, pesticides, and climate change as the main drivers [5]. Their conclusions are contested for relying on non-random samples and regional data. A meta-analysis of 166 long-term surveys by van Klink and coauthors found that terrestrial insect abundance declined about 9 percent per decade while freshwater insect abundance increased, which shows that trends differ by habitat and region [6].

Demand is rising at the same time. Aizen and Harder reported that the global stock of managed honey bee colonies grew about 45 percent over five decades while the area of pollinator-dependent crops grew about 300 percent [7]. On these figures, the pollinator-dependent crop area per managed hive rose by a factor of about 2.8 (4.00 divided by 1.45, an illustrative calculation). Honey bees alone cannot keep pace, and wild pollinators carry a growing part of the load.

This paper reviews how pollinator diversity is measured, how it relates to yield, which landscape and management factors shape it, and what threatens it. The aim is to separate well-supported claims from those that go beyond the evidence.

Research Objectives

- To review the metrics and sampling methods used to assess insect pollinator diversity.
- To compare the contributions of managed and wild pollinators to crop yield and quality.
- To evaluate evidence on whether pollinator diversity, as opposed to abundance, raises yield.
- To assess landscape and habitat effects, including evidence relevant to India.
- To identify the drivers of decline, and to propose an assessment protocol and priorities for future research.

II. LITERATURE REVIEW

2.1 Measuring Pollinator Diversity

Diversity is not a single quantity. Hill's unified notation defines diversity of order q, which differs in how strongly rare species are weighted [8]. Jost showed that the "effective number of species" from Hill numbers behaves intuitively and that raw Shannon and Simpson indices do not, since doubling the effective number of species should double the index [9]. For a community with relative abundances p_i, the effective number is qD = (Σ p_i^q)^(1/(1−q)), with q = 0 giving species richness, q = 1 the exponential of Shannon entropy, and q = 2 the inverse Simpson concentration.

An illustration shows why the order matters. Consider a community of four bee species with abundances of 50, 30, 15, and 5 individuals. Richness (q = 0) is 4. The exponential of Shannon entropy (q = 1) is exp(1.142) ≈ 3.13, and the inverse Simpson index (q = 2) is 1/0.365 ≈ 2.74. Richness treats the rare fifth-percentile species as equal to the dominant one, whereas q = 2 shows that the community behaves as if it had fewer than three equally common species. These numbers are an example from assumed counts, not from a study.

Sampling effort confounds comparisons, because larger samples find more species. Chao and coauthors developed rarefaction and extrapolation of Hill numbers based on sample completeness, which allows communities to be compared at equal coverage instead of equal sample size [10]. Methods also bias what is found. Westphal and coauthors compared bee-sampling methods

across European habitats and showed that pan traps and transect walks capture different parts of the community and that standardized protocols are needed for comparison across regions [11]. The practical consequence is that studies using different methods or different diversity orders are not directly comparable.

2.2 Contributions of Managed and Wild Pollinators, and What Is at Stake

Honey bees are the most frequent visitor to crop flowers globally, but wild insects matter in their own right. Garibaldi and coauthors synthesized data from 41 crop systems and about 600 fields on five continents and found that wild insect visitation enhanced fruit set about twice as much as honey bee visitation and that honey bees did not replace wild insects [12]. Rader and coauthors compiled 39 field studies and showed that non-bee insects, mainly flies, beetles, and butterflies, make a substantial share of flower visits, on the order of 25 to 50 percent as many as bees, and that they are less effective per visit but contribute meaningfully because they are abundant and visit many species [13]. Reilly and coauthors measured seven pollinator-dependent crops in the United States and found that yields were frequently limited by insufficient pollinator visitation, which suggests that pollination deficits are not hypothetical on commercial farms [14].

Pollination also affects quality and market value. Klatt and coauthors showed that bee pollination improved strawberry quality, including fruit shape, redness, firmness, and shelf life, which raises commercial value beyond what yield alone measures [15]. Bommarco, Marini, and Vaissière found that insect pollination increased seed yield, quality, and market value in oilseed rape [16]. For managers, quality effects should be added to the economic benefit of pollination.

The nutritional stakes extend past income. Eilers and coauthors linked crop production data with nutrient composition and found that pollinator-dependent crops supply a large share of dietary vitamin C and other micronutrients, in some cases the great majority [17]. Smith and coauthors modeled the health consequences of current pollinator deficits and estimated about 427,000 excess deaths a year from reduced consumption of fruits, vegetables, and nuts and seeds [18]. This is a modeling estimate with wide uncertainty and depends on assumptions about how diets would adjust.

Pollinator effectiveness depends on more than visit frequency. Ne'eman and coauthors distinguished effectiveness (the contribution per visit) from efficiency (the contribution relative to the cost to the plant) and recommended that pollinator performance be measured as visitation rate multiplied by per-visit effectiveness [19]. A rare but highly effective species can contribute more than a common, ineffective one, and counting visitors alone can mislead.

2.3 Does Diversity Raise Yield?

Several field studies show a positive link between diversity and crop outcome. Klein, Steffan-Dewenter, and Tscharntke showed that fruit set of highland coffee increased with the diversity of pollinating bees [20]. Hoehn and coauthors found that the diversity of bee functional groups increased pumpkin yield [21]. Brittain, Williams, Kremen, and Klein reported that non-*Apis* bees interacting with honey bees improved almond pollination beyond what either would deliver alone, through changes in honey bee foraging behavior [22]. Garibaldi and coauthors analyzed 344 fields from 33 studies and found that flower-visitor richness raised yield in both small and large fields, with small fields tending to hold richer visitor communities [23]. Dainese and coauthors synthesized 89 studies and concluded that increased richness of pollinators and of natural enemies of pests improved crop production [24].

A countervailing finding limits the strength of the diversity argument. Kleijn and coauthors analyzed visitation data from 90 crop systems and found that a small fraction of species, about 2 percent in the typical system, delivered roughly 80 percent of crop flower visits, and that these were common, widespread species [25]. Their conclusion was that crop pollination alone is an insufficient argument for conserving rare wild pollinators. Winfree and coauthors reconciled the two views: although few species dominate at any one site and time, the dominant species differ across sites and years, so many species are needed across a region to maintain services [26]. This suggests that diversity acts as insurance, with its value showing up at larger spatial and temporal scales than a single-field survey.

2.4 Landscape, Habitat, and Management Effects

Proximity to natural habitat supports pollinators. Kremen, Williams, and Thorp studied watermelon farms in California and found that native bees alone could supply full pollination on farms near natural habitat, but not on farms far from it [27]. Ricketts and coauthors synthesized 23 studies and reported that pollinator richness and visitation declined with distance from natural habitat, consistently across systems [28]. Carvalheiro and coauthors found that pollination services declined with

distance from natural habitat even in a biodiversity-rich region, in mango and sunflower in South Africa [29]. Morandin and Winston reported that Canadian canola farms near natural habitat earned more because of better pollination, which gives an economic argument for retaining uncultivated land [30].

Management can restore resources. Blaauw and Isaacs showed that flower plantings adjacent to blueberry fields raised wild bee abundance and improved pollination of the crop [31].

Evidence from India is more limited. India has three native honey bee species and the introduced *Apis mellifera*, along with a large and poorly documented fauna of wild bees, flies, and butterflies [32]. Basu and coauthors studied wild bee diversity in heterogeneous tropical agricultural landscapes in eastern India and found that diversity was shaped by factors at both local and landscape scales [33]. The evidence base for yield effects on Indian crops is thinner than for temperate crops, so claims about India rely partly on extrapolation.

2.5 Drivers of Decline

Potts and coauthors identified five main drivers of pollinator decline: habitat loss and fragmentation, agrochemicals, pathogens and parasites, invasive species, and climate change, with interactions among them [34]. Goulson, Nicholls, Botías, and Rotheray argued that bee declines come from the combined stress of parasites, pesticides, and lack of flowers, so that a single factor rarely explains a loss [35].

Neonicotinoid insecticides have the most direct experimental evidence. Whitehorn and coauthors exposed bumble bee colonies to field-realistic levels of imidacloprid and found that colony growth was reduced and queen production fell by about 85 percent [36]. Rundlöf and coauthors compared fields of oilseed rape with and without clothianidin seed treatment in Sweden and reported reduced wild bee density, solitary bee nesting, and bumble bee colony growth and reproduction in treated fields [37]. Woodcock and coauthors ran field experiments in the United Kingdom, Germany, and Hungary and found that effects varied by country, with negative effects on honey bee colonies in two of the three, so that responses depend on context [38].

Managed colonies are also under strain. Kulhanek and coauthors reported total annual honey bee colony losses of about 40 percent in the United States in 2015–2016, which beekeepers offset by splitting colonies [39]. Zattara and Aizen analyzed worldwide occurrence records and reported that the number of bee species recorded in recent decades fell, with about 25 percent fewer species reported from 2006 to 2015 than before the 1990s, although record-based trends are sensitive to sampling effort [40]. Dicks and coauthors surveyed experts, who ranked land-use change, intensive agriculture, and pesticide use as the leading drivers of pollinator decline [41].

2.6 Assessment Protocols and Research Gap

The Food and Agriculture Organization (FAO) published a handbook for detecting pollination deficits in crops, which compares yield under open pollination with yield after supplemental hand pollination and under pollinator exclusion [42]. The protocol quantifies two things: dependence (how much yield is lost without pollinators) and deficit (how much yield is lost under current conditions relative to full pollination).

The gap is integration. Studies measure diversity, visitation, or yield, and few link all three on the same farms with an economic valuation. Evidence from tropical and Indian systems is scarce. This review addresses the gap with two comparative tables and a protocol that links the measures.

III. METHODOLOGY

This study is a qualitative, comparative review with a conceptual synthesis step. Studies were included if they (i) measured insect pollinator diversity, abundance, or visitation in relation to crop yield, quality, or value, or assessed drivers of pollinator change; (ii) used field data, meta-analysis, or global assessment; and (iii) appeared in a peer-reviewed journal, an established book, or an intergovernmental or FAO publication. Studies were compared along four axes: crop and setting; pollinator measure (richness, visitation, functional diversity, or abundance); outcome (yield, quality, or value); and study design (observational, experimental, or synthesis). Reported figures are those of the original authors, are not re-estimated, and are not comparable across studies because crops, regions, and methods differ. Illustrative calculations (Hill numbers, hive-to-crop ratio, and economic examples) use stated or assumed inputs and are labeled as such. No new field data are reported, and because most evidence comes from temperate systems, claims for tropical systems, including India, are extrapolations.

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IV. RESULTS AND DISCUSSION

4.1 Evidence on Diversity, Visitation, and Yield

Table 1 maps the principal studies onto crop, pollinator measure, and finding.

Table 1. Pollinator Diversity, Visitation, and Crop Outcomes: Reported Findings

Study Focus	Crop or Setting	Pollinator Measure	Reported Finding	Ref.
Global dependence	115 leading food crops	Crop dependence classes	87 benefit; about 35% of production volume	[1]
Wild vs. managed	41 crop systems, about 600 fields	Visitation by wild insects and honey bees	Wild insects raised fruit set about twice as much; no substitution by honey bees	[12]
Non-bee insects	39 field studies	Visits by non-bee taxa	Substantial share of visits; less effective per visit	[13]
Pollination limitation	Seven U.S. crops	Yield vs. pollinator visits	Yields frequently limited by insufficient visitation	[14]
Quality	Strawberry	Bee pollination	Better shape, redness, firmness, shelf life	[15]
Diversity	Highland coffee	Bee diversity	Fruit set increased with diversity	[20]
Functional diversity	Pumpkin	Bee functional groups	Yield increased with functional-group diversity	[21]
Species interactions	Almond	Honey bees with non-*Apis* bees	Improved pollination beyond either alone	[22]
Farm size	344 fields, 33 studies	Flower-visitor richness	Richness raised yield in small and large fields	[23]
Dominance	90 crop systems	Share of visits by species	About 2% of species gave roughly 80% of visits	[25]
Regional turnover	Multiple systems	Species identity across space and time	Different species important in different places and years	[26]
Distance from habitat	Watermelon; mango, sunflower	Visitation and richness	Services fall with distance from natural habitat	[27], [28], [29]

4.2 Discussion: What the Evidence Supports

Table 1 supports four conclusions. First, dependence is real but crop-specific. Pollination affects about 35 percent of production volume but a much smaller share of calories, since staple cereals are wind-pollinated [1]. The nutritional and economic stakes therefore fall mostly on fruits, vegetables, nuts, oilseeds, and some beverage crops [17], [18].

Second, honey bees and wild insects are complements. The finding that wild insects raised fruit set about twice as much as honey bees, with no substitution, means that adding hives does not compensate for wild-pollinator loss [12]. The mismatch between a 45 percent increase in hive numbers and a roughly 300 percent increase in pollinator-dependent crop area shows that managed bees are being asked to do more per hive, and the Reilly results show that deficits already occur on commercial farms [7], [14].

Third, the case for diversity depends on scale. At one site and time, a few common species do most of the work, as the Kleijn analysis shows [25]. But the Winfree result that dominant species change across space and time means that a regional diversity of species is what keeps services stable [26]. The interaction effects in almond and the functional-group results in pumpkin

suggest that diversity also adds complementarity through different foraging behaviors [21], [22]. A fair summary is that diversity is not needed for average yield in every field, but it works as insurance for yield stability and for the regional resilience of the service.

An illustrative calculation shows the logic of insurance. Suppose a crop is served by five equally effective species that each have an independent 20 percent chance of being absent in a given year. The probability that all five are absent is $0.2^5 = 0.00032$, whereas a single species is absent 20 percent of the time. Real species respond to shared drivers such as weather and pesticides, so independence overstates the benefit, but the example shows why variety lowers year-to-year variance. The inputs are hypothetical.

Fourth, the measurement limits are substantial. Most quantitative studies use temperate crops and visitation as the pollinator measure, and visitation is an imperfect proxy for effectiveness [19]. Studies with richness at $q = 0$ can overstate the role of rare species relative to studies that weight by abundance [8], [9].

4.3 Threats, Evidence, and Mitigations

Table 2 sets the principal threats against the evidence and mitigations.

Table 2. Threats to Pollinator Diversity: Evidence and Mitigation

Threat	Evidence Reviewed	Mitigation	Ref.
Habitat loss and distance from natural habitat	Visitation and richness decline with distance from natural habitat	Retain and connect semi-natural habitat	[27], [28], [29], [30]
Insecticides, especially neonicotinoids	Queen production about 85% lower; reduced wild bee density in treated fields; effects vary by country	Reduce or time applications; use integrated pest management	[36], [37], [38]
Combined stressors	Parasites, pesticides, and lack of flowers act together	Manage multiple stressors jointly	[34], [35]
Floral resource shortage	Flower plantings raised wild bee abundance	Flower strips; hedgerows; cover crops	[31]
Managed colony losses	About 40% annual U.S. colony loss, 2015–2016	Colony health programs; reduce reliance on single species	[39]
Overall insect decline	76% biomass decline in German reserves; about 9% per decade terrestrial	Monitoring with standard methods	[4], [6]
Evidence gaps	Record-based and regional trends sensitive to sampling	Standardized sampling and coverage-based comparison	[10], [11], [40]
Demand growth	Pollinator-dependent area up about 300% vs. hives up about 45%	Diversify pollinator sources	[7]

4.4 Discussion: Interpreting the Decline and Acting on It

Table 2 shows that pressures are interacting and unevenly documented. The experimental pesticide evidence is stronger than the evidence for many other drivers, since the Whitehorn and Rundlöf results come from controlled or paired designs, but the Woodcock results show that the effects are context-dependent and that no single country's result can be generalized [36], [37], [38].

Trend evidence needs care. The 76 percent biomass decline in German reserves is large and well-measured but applies to flying insect biomass at specific sites, not to pollinators globally [4]. The meta-analysis showing roughly 9 percent per decade for terrestrial insects, and increases in freshwater insects, makes clear that trends differ by habitat and region [6]. Record-based bee declines depend on sampling effort [40]. A defensible statement is that there is strong evidence of declines in many regions and groups, and weaker evidence for global pollinator-specific trends.

Management implications follow from the habitat evidence. Natural habitat near fields supports services, and flower plantings can raise wild bee numbers [27], [31]. Morandin and Winston's profit result suggests that retaining uncultivated land has an economic return in some systems, which should be tested before it is assumed for others [30]. Reducing insecticide exposure, particularly during bloom, addresses the best-documented driver [36], [37].

India-specific implications are mostly inferential. With limited local evidence on yield effects, the sensible course is to measure first. The protocol below is designed for that purpose.

4.5 A Farm-Level Assessment Protocol

The reviewed evidence suggests a protocol that links diversity, visitation, deficit, and value. It is a conceptual synthesis from the evidence above and has not been tested.

1. **Survey the community.** Sample with a standardized combination of pan traps and transect walks, with equal effort per site and season [11].
2. **Compute diversity at several orders.** Report Hill numbers at q = 0, 1, and 2 at equal sample coverage, so that rare and dominant species are both represented and sites are comparable [8], [9], [10].
3. **Measure visitation and effectiveness.** Record visits per flower per unit time by taxon, and measure per-visit pollen deposition or fruit set from single visits to estimate effectiveness, so that the contribution of each taxon is visitation multiplied by effectiveness [19].
4. **Measure dependence and deficit.** In each field, compare yield under pollinator exclusion, open pollination, and open pollination with supplemental hand pollination [42]. Define dependence D = 1 − (yield without pollinators ÷ yield with open pollination) and deficit = 1 − (yield under open pollination ÷ yield with supplemental pollination).
5. **Value the service.** Multiply D by crop revenue to estimate the value of current pollination, and multiply the deficit by revenue to estimate the gain from closing it, following the valuation logic of Gallai et al. [3]. Include quality effects where measured [15], [16].
6. **Test interventions.** Add flower strips or reduce insecticide use in a subset of fields, and compare diversity, deficit, and yield with controls in a before–after design [30], [31].
7. **Assess stability across years and sites.** Track which species dominate each year and whether yield variance falls with regional richness, to test the insurance argument [26].

As an illustration with assumed values, consider a 10-hectare field of a pollinator-dependent crop yielding 20 tonnes per hectare under open pollination, sold at $500 per tonne, so revenue is $100,000. If D = 0.30, then yield without pollinators would be 0.7 × 20 = 14 tonnes per hectare, and the pollination contribution is $30,000 per year on those assumptions. If the deficit is 15 percent, full pollination would yield 20 ÷ 0.85 ≈ 23.5 tonnes per hectare, a gain of 3.5 tonnes per hectare, or about $17,600 across 10 hectares. A flower strip that closes half the deficit and costs less than about $8,800 a year would then pay for itself on pollination alone. These numbers are hypothetical, and real values must be measured field by field.

V. CONCLUSION

This paper reviewed evidence on insect pollinator diversity and agricultural productivity. Three conclusions follow. First, pollination contributes materially to production and nutrition: 87 of 115 leading crops benefit, about 35 percent of volume depends on it, and the attributable annual value is estimated at $235 to $577 billion [1], [2]. Second, wild insects and honey bees are complementary rather than interchangeable: wild insects raised fruit set about twice as much as honey bees, and managed hive growth of 45 percent has lagged a roughly 300 percent expansion in pollinator-dependent crop area [7], [12]. Third, the diversity argument is strongest at regional and multi-year scales, where species turnover keeps services stable, and weaker for the average single field, where a few common species deliver most visits [25], [26]. Pressures from habitat loss, insecticides, and combined stressors are documented, though the strength of evidence varies by driver and region [4], [6], [36], [37]. The practical recommendation is to measure pollination deficit and diversity on farms, retain and restore habitat, reduce insecticide exposure during bloom, and avoid relying on a single managed species.

VI. FUTURE WORK

Future research should prioritize several areas. First, field studies linking diversity, visitation, deficit, and yield on the same farms are needed for tropical and Indian crops, where evidence is thin [32], [33]. Second, methods should be standardized, with coverage-based diversity comparison and common sampling protocols, so that studies can be combined [10], [11]. Third, experiments on interventions such as flower strips and insecticide timing should measure yield and profit over several years, extending the existing results for blueberry and canola [30], [31]. Fourth, work should test the insurance value of diversity directly, by measuring whether regional richness reduces yield variance [26]. Finally, the protocol in Section 4.5 should be piloted on a set of farms to see whether its measurements predict where interventions pay.

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