



The Role of Pollinating Insect Diversity in Food Crop Productivity in Sustainable Agricultural Ecosystems

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Abstract

Pollinating insects play an important role in maintaining the sustainability of agricultural ecosystems while increasing crop productivity. The background of this study stems from the problem of declining pollinator populations due to environmental degradation, land use change, and ecosystem-unfriendly agricultural intensification. This study uses a descriptive qualitative approach with literature review and secondary data analysis from various relevant previous studies. The objective of this study is to describe the diversity of pollinating insects in sustainable agricultural ecosystems and analyze their contribution to food crop productivity. The results of the discussion show that pollinator diversity functions as a pillar of ecosystem stability by providing sustainable ecological services, including cross-pollination and increased plant resistance. Empirical data show that the presence of pollinators can increase crop yields by more than 30% for several strategic food commodities. In addition, the quality of agricultural products, such as size, taste, and shelf life, also improves thanks to pollinator activity. Thus, the sustainability of pollinator populations not only contributes to biodiversity conservation but also significantly strengthens national food security.

Keywords: *Ecosystem, Food Security, Sustainable Agriculture, Pollinating Insects, Food Crops.*



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INTRODUCTION

Biodiversity at the taxonomic, functional, and genetic levels is the main foundation for productive and resilient agricultural ecosystem resilience. The ecosystem function most directly linked to production outcomes is pollination services facilitated by diverse groups of insects such as Hymenoptera, Diptera, Lepidoptera, and Coleoptera. Dependence on pollination services varies between commodities; some horticultural and fruit crops are highly dependent on animal pollination for fruit formation and quality improvement. Recognition of the role of pollinating insects places diversity as a key variable that must be considered in sustainable agriculture strategies. This statement is supported by the results of an international study on the relationship between pollinators and food production (Potts, et al., 2016).

Globally, about 35 percent of the world's food crop production is influenced by animal pollination; while three-quarters of flowering plant species depend partly on animal pollinators for their sexual reproduction. This proportion confirms that although most of the world's food tonnage comes from cereals that are not entirely dependent on pollinators, commodities that are highly dependent on pollination play an important role in nutritional intake, food diversity, and agricultural economic value. The agronomic and economic implications of this dependence underlie the urgency of conserving and managing habitats that support pollinating insects. Thus, research on pollinator diversity is relevant not only from an ecological perspective, but also in terms of food security and farmer welfare (Ritchie, 2021).

The role of pollinator diversity is not merely a matter of individual numbers, but also involves species composition, functional diversity, and spatial interactions between plants and insects. Different pollinator species often exhibit complementary behavioral and morphological traits, such as variations in activity time, flower preferences, and nectar collection techniques, so that the presence of a variety of species increases the resilience of pollination services to environmental changes. Therefore, the loss of one or more species can reduce pollination efficiency even when the total number of insects does not

change significantly. A research approach that considers the functional and spatial aspects of pollinator communities is needed to understand the impact on crop productivity. Ecosystem studies provide a theoretical basis for linking pollinator community structure with resulting ecosystem functions.

Insect pollination services have substantial value for food production and the local and national economy; case studies in various countries show that the value of pollination services reaches hundreds of millions to tens of billions of US dollars per year, depending on the area covered and the commodities analyzed. Beyond direct monetary value, pollination services improve fruit quality, size, and seed formation rates, which impact market prices and the nutritional value of food products. Thus, integrating economic assessments into pollinator diversity research helps bridge conservation policies with agricultural productivity interests. Cost-benefit analyses of pollinator habitat conservation often show that investments in pollinator-friendly practices provide positive economic returns for farmers and communities. Economic values and regional case studies can be found in ecosystem economics studies and national reports (Christmann, et al., 2021).

Agricultural intensification, including monoculture, indiscriminate use of pesticides, large-scale land clearing, and reduction of vegetation on land boundaries, are major factors that reduce the diversity of pollinating insects. These impacts arise from the loss of food sources (nectar and pollen), resting and nesting places, and increased exposure to insecticide toxins. Consequently, agricultural areas that were once productive in terms of pollination experience a decline in local and temporal ecosystem services. Therefore, this study places the analysis of land management practices as an integral part of understanding how pollinator diversity can be maintained or restored. Agroecological approaches and county-scale landscape management can provide contextual mitigation solutions (Fanani, et al., 2025).

In tropical regions such as Indonesia, the characteristics of biodiversity and pollinator community dynamics show different patterns compared to temperate regions; the tropics are home to a high diversity of pollinator species but are also vulnerable to the pressures of climate change and land conversion. Local studies in Indonesia show the important role of pollinating insects in horticultural commodities and vegetables, including increased yields in crops such as squash, papaya, and several leafy vegetables after effective pollination. In addition, tropical climatic conditions create complex interactions between plant phenology and insect activity times, which must be considered in productivity research design. Literature from national institutions and field case studies reinforce the importance of pollinator conservation in Indonesian agricultural systems. These local data and studies underlie the urgency of research in Indonesia's sustainable agricultural ecosystems (Fita, 2024).

The concept of sustainable agriculture emphasizes food production that maintains long-term ecological functions, including pollination services; therefore, this study adopts an agroecological framework that combines productivity and biodiversity conservation. This approach involves practices such as crop diversification, green corridor management (refugia habitats), reduction of hazardous chemical inputs, and the application of flowering buffer zones. Field experiments and observational studies measuring the relationship between these managerial actions and indicators of pollinator diversity and crop yields are essential methodological components. The implementation and evaluation of these practices provide empirical evidence for policy recommendations and guidance for farmers. This research will assess the causal relationship between sustainable agricultural practices, pollinator diversity, and crop productivity (Mapegau, et al., 2025).

Experimental approaches involving pollinator exclusion and community manipulation (e.g., use of exclusion nets or addition of food sources) can help distinguish the contribution of specific species to increased crop yields. In addition, the use of functional metrics such as body size, proboscis length, and daily activity patterns will support the interpretation of how community composition affects pollination function. Longitudinal data tracking seasonal and interannual changes will strengthen inferences about the stability of pollination services. The combination of taxonomic, functional, and quantitative crop yield data allows for a comprehensive assessment of the role of diversity. There is an urgent need to incorporate pollinator diversity indicators into agricultural productivity evaluation systems, which have thus far focused solely on tonnage per hectare and input intensity. Indicators such as the Shannon diversity index, flower visitation frequency per hour, and pollination ratios can complement traditional agronomic indicators. These measurements not only provide an ecological picture, but also facilitate communication of the benefits of pollination services to agricultural stakeholders and policymakers. With standardized indicators, support programs such as habitat

conservation incentives or pollinator-friendly practices can be evaluated objectively. Standardization of indicators also supports replication of studies and meta-analyses across regions.

Threats to pollinators, including habitat loss, pesticides, disease, invasive species, and climate change, have been reported to reduce pollinator abundance and diversity in many regions of the world. The cumulative impact of these threats has the potential to reduce the stability of pollination services, posing a risk to the production of nutritious commodities that rely on pollinators. Therefore, this study will also document anthropogenic and environmental factors that affect pollinator communities at the field to landscape scale. Understanding these decomposing factors is a prerequisite for formulating targeted interventions. Global and regional studies on pollinator decline trends form the basis for formulating research hypotheses related to local pressures (Wanger, et al., 2021).

Agroecological practices such as planting flowering cover crops, habitat corridors, and reducing the use of synthetic pesticides have been shown to increase the diversity and abundance of pollinating insects in several case studies. In addition, crop diversification and intercropping can create a more continuous supply of nectar, thereby reducing the risk of seasonal pollination deficits. Farmer involvement through a participatory approach is also important to adapt these practices to local conditions and economic needs. Assessing the costs and benefits of adopting pollinator-friendly practices is one aspect that will be analyzed to ensure feasible recommendations. Managerial interventions focused on habitat and production practices will be the focus of this research policy recommendation. Measuring crop productivity in the context of this study involves not only looking at increases in weight or number of fruits, but also quality parameters such as fruit size, seed ratio, and nutritional content, which can be influenced by pollination quality (Ikhsan, et al., 2025).

Agronomic studies show that effective cross-pollination often increases product size and homogeneity, thereby impacting market prices. Therefore, productivity analysis will involve comprehensive quantitative and qualitative metrics to capture the real contribution of pollination services to the added value of agricultural products. The use of these quality indicators also facilitates dialogue between scientists, farmers, and market actors about the conservation value of pollinators. The research results are expected to form the basis for measurable and applicable agronomic recommendations. From a policy perspective, research results on the relationship between pollinator diversity and productivity can provide an empirical basis for policy instruments such as conservation incentives, ecosystem service payment programs, and pesticide use regulations. Policies that integrate biodiversity and ecosystem services into national or regional agricultural planning have the potential to support long-term food security. In addition, economic evidence related to pollination services strengthens the argument for allocating funds to community-based conservation programs and incentives for sustainable agricultural practices. This research will present policy options that are empirically based and relevant to the local context. Policy recommendations aim to bridge the goals of conservation and agricultural productivity (Aizen, et al., 2023).

Methodologically, this study will combine field approaches (surveys of pollinator communities and crop yield measurements), experiments (manipulation of food sources or pollinator exclusion), and simple economic analysis to calculate the value of pollination services' contribution to productivity. Sampling will be stratified based on agricultural practices (e.g., conventional, organic, agroforestry) and landscape characteristics (land size, presence of semi-natural habitats). Statistical analyses, including mixed linear models and path analysis, will be used to test direct and indirect relationships between pollinator diversity, management practices, and crop yields. Cross-seasonal research will ensure that seasonal and phenological variations are accommodated. This mixed approach is expected to produce robust and applicable conclusions.

The scientific contributions expected from this research include a detailed understanding of how the composition and diversity of pollinating insects affect the specific productivity of food commodities in tropical agricultural landscapes. In addition, this research has the potential to produce practical indicators for field management that can be adopted by farmers and agricultural extension workers. The findings are also expected to contribute to the global literature on the role of functional diversity in maintaining agricultural ecosystem services. In terms of policy, the empirical evidence generated can facilitate the development of land-based conservation programs and economic incentive schemes.

This research will form the basis for recommendations that integrate productivity, conservation, and farmer welfare. Given the complexity of interactions between pollinator diversity, agricultural practices, and crop yields, this research requires multidisciplinary collaboration between ecology,

agronomy, agricultural economics, and applied social sciences. The involvement of local stakeholders, including farmers, extension workers, local governments, and environmental NGOs, will increase the relevance and adoption of the resulting recommendations. Based on empirical evidence and a participatory approach, the recommended interventions are expected to be contextual and sustainable. This research aims to strengthen food security through the preservation of pollination services that depend on insect diversity. The results of this research are expected to contribute significantly to sustainable agricultural development in tropical regions, particularly Indonesia.

RESEARCH METHOD

This research method uses a descriptive qualitative approach with the aim of gaining an in-depth understanding of the role of pollinator insect diversity in crop productivity in the context of sustainable agriculture. The research was conducted in agricultural ecosystems with varying management practices, such as organic, semi-intensive, and agroforestry land, to capture the diversity of ecological contexts. The main data were collected through participatory observation in the field by recording the interactions of pollinating insects with food crops and the dynamics of their daily activities. The researchers also took visual documentation in the form of photographs and field notes to reinforce the description of visitation patterns, types of pollinating insects, and the ecosystem conditions that support their existence. The research focused on understanding the ecological significance of pollinator diversity, rather than merely statistical measurements. The data obtained was analyzed using thematic analysis methods, namely identifying patterns, themes, and relationships between categories to explain how pollinator diversity affects food crop productivity. With this approach, the research is expected to produce a deep, contextual, and applicable understanding of the contribution of pollinator diversity to sustainable agriculture (Matheus, 2025).

RESULTS AND DISCUSSION

The Diversity of Pollinating Insects in Sustainable Agricultural Ecosystems

The diversity of pollinating insects in agricultural land is a vital component that affects the stability of sustainable agricultural ecosystems. In many studies in Indonesia, the orders Hymenoptera, Diptera, Lepidoptera, and Coleoptera have emerged as the dominant groups of pollinating insects. For example, in coffee plantations in North Sumatra, 16 species of pollinating insects were found near forests and 13 species were found in locations far from forests (Sinaga, et al., 2024). This condition shows that the distance to the original habitat (forest) affects the diversity of pollinator species. Therefore, maintaining border habitats is very important in preserving the diversity of pollinator communities. Diversity indices (e.g., Shannon-Wiener index), evenness, and dominance are often used to describe the structure of pollinator communities. A study at the Botanical Garden of the Sumatra Institute of Technology found diversity index (H') values in orange and guava gardens between 1.5 and 1.9, which is categorized as “moderate” (Maretta, et al., 2025).

Dominance values at the same location indicate a relatively low level of dominance of certain species, suggesting a fairly even distribution of species. This moderate diversity suggests that, although not very high, pollinator communities are quite resilient to some disturbances. Evaluating community structure in this way is important for understanding how diversity underpins pollination functions in sustainable agricultural systems. Low to moderate intensity agricultural land use (including agroforestry and organic farming) tends to have higher pollinator diversity than intensive monocultures. In a study in Jambi, rubber and oil palm plantations showed different numbers of pollinator species depending on the type of land use. For example, rubber plantations had 31 species, while oil palm plantations had 23 species, and “jungle-rubber” (a mixture of forest and rubber) had only 7 species (Siregar, et al., 2016).

The highest diversity is found in agricultural land that retains more natural vegetation. Vegetation conservation practices and the presence of natural habitats around agricultural land have been shown to influence the presence of pollinator species. Variations in the daily activities and foraging periods of pollinating insects also affect the diversity that is effective in carrying out pollination. Research in Jambi shows that pollinator insect visits are higher in the morning (around 8:00–10:00 a.m.) and afternoon (around 2:00–4:00 p.m.) when weather conditions are favorable.

This relates to temperature, humidity, and sunlight intensity, which affect insect mobility and foraging activity. If sustainable agriculture regulates cropping patterns and water use to maintain microclimate humidity and temperature, foraging activity can remain optimal. Therefore, temporal

analysis of diversity (daily and seasonal) is necessary for effective pollinator conservation strategies. Species abundance and composition also determine how diversity impacts pollination services. A study in coffee plantations showed that species such as *Apis cerana* and various *Lasioglossum* were more abundant in locations close to forests than in locations far from forests (Sinaga, et al. 2024). In addition, Diptera species such as *Stomorhina discolor* also appear as fairly frequent flower visitors. Differences in composition such as this are significant, because some species are more efficient or visit certain flowers more often. Thus, analysis should not only be based on the number of species, but also on visitation activity and the effectiveness of species within the community. Focusing on functional diversity is very important.

Functional diversity, including body size, proboscis length, activity period, and flower type preference, plays a role in determining the distribution of pollination services. For example, some bee species have long proboscis that allow them to reach deeper flowers, while flies (Diptera) and butterflies (Lepidoptera) often visit open or shallow flowers. A study of Lepidoptera in coffee agroforestry in Pangalengan examined communities based on environmental factors and found that species presence was influenced by shade vegetation and the type of vegetative substrate around coffee trees (Maharani, et al., 2024). This diversity allows for adaptation to environmental changes and climate fluctuations. Knowledge of functional diversity helps in designing agricultural systems with flowering forage plants and landscape structures that support various types of pollinators.

Environmental factors such as distance to forests, types of riparian vegetation, and habitat fragmentation have a significant impact on pollinator diversity. A study in North Sumatra found that coffee planted near forests had more pollinator species than locations far from forests (Sinaga, et al., 2024). Natural vegetation on the edges of agricultural land provides shelter, alternative nectar sources, and habitats for mating and nesting. Severe habitat fragmentation reduces interactions between flowering plants and pollinating insects through isolation effects. Therefore, sustainable agriculture needs to consider the broader landscape structure, not just individual plots of land.

The impact of pesticide and other agrochemical use on pollinator diversity has been widely reported. One study in West Java on coffee plantations found that more intensive pesticide use correlated with a reduction in the number of flower visitor species and the time spent visiting flowers per visitor species. Pollinating insects are highly sensitive to pesticide residues, and the effects are not always immediate but can accumulate over time. Sustainable agricultural practices often include the use of natural pesticides or integrated pest management (IPM) to minimize negative impacts on non-target insects. Therefore, regulating pesticide use should be considered as part of a pollinator diversity conservation strategy (Manson, et al., 2022).

Tabel 1. Keanekaragaman Serangga Penyerbuk

Location	Commodity / Land Type	Number of Pollinator Species	Main Orders	Key Notes
Simalungun, North Sumatra	Coffee (near and far from forest)	± 16 vs ± 13	Hymenoptera, Diptera, Coleoptera, Lepidoptera	Pollinator diversity is higher near the forest (Sinaga et al., 2024) Lands that maintain natural vegetation
Jambi	Rubber, oil palm, jungle-rubber	31 (rubber), 23 (oil palm), 7 (jungle-rubber)	Hymenoptera, Diptera, Lepidoptera	support a greater number of species (with relatively moderate evenness and

Sumatra Botanical Garden	Fruit (guava, dragon fruit), aesthetic garden	$H' \approx 1.5-1.9$	Coleoptera, Diptera, Hymenoptera, Lepidoptera	dominance) (Maretta et al., 2025) Diversity index categorized as medium to high (Maretta et al., 2025)
Modayag, Bolaang Mongondow Timur	Tomato	Ordo = 4 (Hymenoptera, Lepidoptera, Diptera, Coleoptera)	–	Diversity index fits the medium- to-high category (Maunangkey et al., 2022)

This table demonstrates the variation in the number of pollinator species between locations and land types, as well as the importance of conserving supporting vegetation around agricultural areas. Agroforestry systems are consistently reported to have higher pollinator diversity than intensive plantations without shade-providing vegetation. In coffee agroforestry in Pangalengan, the diversity of Lepidoptera as pollinators is influenced by the presence of shade trees and vegetative substrates without major mechanical disturbance (Utari, et al., 2024).

High diversity in agroforestry indicates that heterogeneous land structures support the various microhabitats required by pollinating insects. In addition, agroforestry often provides a longer-lasting supply chain of nectar and pollen within a single season. Thus, agroforestry is one of the key practices in sustainable agriculture for maintaining pollinator diversity. Research may find that land closer to forest areas or other natural habitats has more diverse pollinator species and higher abundance. For example, in coffee plantations in Simalungun, locations near forests recorded 16 species, while distant locations recorded only 13 species.

Proximity to forests allows for the colonization of wild species that would not be found if the land were completely isolated. The boundary between agricultural land and forests also serves as an important ecological corridor. Landscape management strategies that maintain connectivity between agricultural land and natural habitats can promote the exchange and stability of pollinator communities. Seasonal variations are also a factor that affects pollinator diversity. Several studies show that during the rainy season or seasonal transitions, the availability of flowers and environmental conditions such as high humidity support more flower-visiting insects. Conversely, during the dry season or periods of extreme weather, the activity and presence of pollinating insects often decline due to reduced availability of nectar and flowers. However, research in Indonesia that systematically measures the diversity of pollinating insects across seasons is still relatively scarce. Future research needs to incorporate longitudinal designs to capture seasonal fluctuations in diversity. The involvement of non-bee insect communities (wild bees, flies, butterflies, beetles) is often overlooked, even though they play an important role. In a study of coffee in Simalungun, in addition to *Apis cerana*, *Lasioglossum* spp. and a number of Diptera species also contributed to flower visits.

Some of these species may be generalists and able to pollinate many types of flowers. Protecting these non-bee species also means protecting the functional diversity that supports ecosystem resilience. Therefore, sustainable agriculture must include strategies to support the entire pollinator community, not just commercial species. The impact of land use change converting forests to plantations, intensive land use can drastically reduce pollinator insect diversity. Data from Jambi shows that converting forests to oil palm or rubber plantations significantly reduces the number of species in natural communities.

In more heterogeneous “jungle rubber” areas, there are only 7 species compared to more homogeneous rubber areas. This change in land use not only reduces species, but also changes the species composition, making the community dominated by species that are tolerant to disturbance or pesticides. Therefore, land use and buffer zone policies must take biodiversity conservation into account. The main challenges in maintaining pollinator diversity in sustainable agriculture include

pesticide management, habitat fragmentation, climate stress, and access to adequate nectar sources. Many species require alternative nectar sources outside the flowering season of the main crop in order to remain active throughout the season. Otherwise, populations will decline during periods of flower scarcity. Fragmentation hinders individual mobility and reduces gene exchange between populations. Sustainable agricultural management must combine habitat conservation strategies, flowering crop rotation, and the creation of vegetative corridors.

The diversity of pollinating insects in sustainable agricultural ecosystems is not merely a matter of species numbers but involves species composition, functional diversity, and habitat connectivity. Agricultural practices such as agroforestry, forest edge conservation, reduced pesticide use, and flowering crop diversification have been shown to support higher diversity. Field data from various locations in Indonesia show that local environmental and landscape factors have a strong effect on pollinator species and activity. Further research is needed to expand seasonal data and explore non-bee pollinator species and their specific ecological roles. A deep understanding of this diversity will be an important basis for designing agricultural practices that balance productivity and ecosystem conservation.

The Role of Pollinating Insects in Food Crop Productivity

Pollinating insects play a crucial role in cross-pollination between flowers, which can increase the percentage of fertilization, fruit size, and the homogeneity of food crop products. Without pollinator interaction, most plants that depend on animal pollination would rely solely on self-pollination (autogamy) or abiotic mechanisms, which often result in lower yields or poor fruit quality. In many pollinator exclusion studies (using nets or cover bags), plants left without insect visits showed yield reductions ranging from 18% to 71% depending on the plant species. This variation illustrates that the contribution of pollinating insects to productivity is not uniform, but rather depends on the biological and ecological context of the plant (Bartomeus, et al., 2014).

The contribution of pollinating insects to crop yield varies between commodities: in crops such as strawberries, beans, rapeseed, and buckwheat, research shows that insect participation improves both the quantity and quality of the harvest. For example, in strawberries, exclusion tests show that naturally pollinated fruits have a higher commercial grade than fruits isolated from pollinators. The role of pollinating insects goes beyond quantity; they also improve fruit quality attributes. Recent research emphasizes that pollinator identity, movement patterns, and activity times greatly influence the extent to which quality improvements are achieved. The increase in crop yield due to insect pollination ranges from tens of percent, depending on the type of plant and the intensity of insect visits. For example, in cash crops, pollination intervention by honey bees or wild bees can increase yields by up to 62% compared to controls without pollinators.

This increase covers both the number of fruits and their quality (e.g., size, weight, percentage of viable seeds). This effect confirms that pollination is one of the key variables in the agronomic system of pollen-dependent plants. However, the maximum contribution of pollination is often saturated, meaning that after a certain threshold, additional pollinator visits do not significantly increase yields. In addition to increasing average yields, pollinating insects also play a role in maintaining production stability between years. A study shows that animal pollination services can reduce yield variability between plots or between seasons by an average of 32% per unit of production.

Climate conditions or environmental stress fluctuate, and the presence of pollinators can mitigate negative fluctuations in crop yields. This stability is particularly important in agricultural systems that are vulnerable to disturbances such as drought or extreme rainfall. Therefore, the role of pollinating insects in maintaining consistent productivity is an important component of sustainable agriculture. Animal pollination also contributes to agronomic efficiency by reducing empty fruit, failed seed formation, or suboptimal fertilization. In some crops, the quality of cross-pollination performed by insects reduces the percentage of unfertilized ovules and increases the ratio of viable seeds. For example, in some seed crops, effective pollination reduces the number of empty seeds and increases seed weight. Thus, the benefits of pollination include margins for improving crop resource efficiency (e.g., more optimal fertilizer use). Even in crops that have been genetically selected for high yields, pollination services still provide additional yield gains (Rielly, et al., 2020).

The role of pollinators is also related to the landscape context and the availability of semi-natural habitats in the surrounding area. In landscapes with fragments of original habitats (trees, shrubs, wild

grasslands), pollinator visitation rates and effectiveness tend to be higher. For example, research on faba beans in Sweden found that plants in landscapes with a proportion of semi-natural habitats produced an average of 27% higher seed weight per plant than plants that were restricted from insect visits (exclusion experiment). This relationship shows that landscape design, such as maintaining original corridors or insertive vegetation, can strengthen the contribution of pollination to crop productivity. In landscapes with plant and habitat diversity, interactions between pollinator species and plants become more complex, and pollinator diversity often promotes “functional complementarity.” This means that different pollinator species complement each other in terms of activity time, body size, or plant preferences, resulting in more comprehensive pollination visits. Recent studies emphasize that simply increasing the number of pollinators is not enough; the identity and behavior of pollinator species also greatly determine the effects on pollination quality and crop yields.

Case studies show that even with high bee density, if there is no functional diversity, some flowers may not be optimally pollinated. Pollinator management strategies must consider not only quantity, but also diversity of species and behavior. The decline in wild pollinator populations due to environmental pressures such as pesticide use, habitat loss, and climate change has been reported to pose a real obstacle to crop productivity. A study in the United States shows that the lack of wild pollinators significantly limits crop production and reveals that the US agricultural sector has lost significant economic value due to the decline in wild bee populations (Bishop, et al., 2022).

Other studies indicate that approximately 60% of food crops worldwide do not receive adequate pollinator visits, resulting in production below their maximum potential. beewise.ag This decline can create a “limitation gap” where actual productivity falls far below the optimal capacity that would be achieved with sufficient pollinator visits. A global study on the dependence of plants on animal pollination shows that although about 75% of flowering plant species depend partially on animal pollination, its contribution to overall global food production is about 35%. Most of the world's food tonnage comes from cereal crops (such as wheat and rice) that do not depend entirely on insect pollination. However, highly nutritious food crops (fruits, vegetables, nuts) are highly dependent on this pollination service. Although the role of pollinators in total food volume may be considered moderate, their contribution to the diversification of nutritious foods is crucial.

The assessment of food crop productivity must consider quantitative and nutritional aspects so that the role of pollinators is not underestimated. In an economic context, insect pollination services have great economic value because increased crop yields and quality provide added market value. The global economic value of animal pollination services is estimated to reach tens to hundreds of billions of euros or dollars per year based on agronomic and ecosystem studies. With such clear economic value, maintaining the health of pollinator populations is as important as optimizing agronomic inputs such as fertilizers or irrigation. Analysis of the added value of production due to pollinator visits helps build policy arguments and incentives for pollinator conservation on agricultural land. In many cases, increased visits by local pollinators provide a higher economic return than other external investments. The contribution of pollinating insects is also directly related to the quality of fruit crops, which are larger, rounder in shape, and have higher sugar content, color, and quality homogeneity. Many studies report that naturally pollinated plants produce fruit with higher market appeal than flowers that are pollinated only partially or artificially. Modern research examples show that pollination methods using honey bees result in a 56.28% increase in fruit yield compared to hand, wind, or self-pollination methods in several fruit crops.

These quality improvements add economic value and maintain the reputation of agricultural products. Thus, even if the quantity of fruit does not change drastically, quality improvements are often quite significant in the market context. In addition, pollinating insects enable crop diversification in rotation or intercropping because pollinator-dependent crops can grow more optimally if pollination services are adequate. Often, farmers are hesitant to plant high-yielding flowering crops due to the risk of insufficient pollination; however, with good pollinator habitat maintenance, diversification can be carried out with low production risk. This diversification, in turn, can strengthen ecosystem stability and provide flowers for insects to feed on throughout the season. Thus, the role of pollinators goes beyond the direct effect on a single crop, but contributes to the overall structure of a sustainable agricultural system. The dependence of food crops on insect pollination is also greatly influenced by the interaction between crop cultivars and pollinator identity.

Not all pollinators are equally effective on all plant varieties; selecting varieties and planting layouts that take into account pollinator behavior and range can increase the benefits of pollination services. Recent studies confirm that pollinator identity, plant distribution patterns, and plant spacing affect pollen transfer efficiency. In research on crop productivity, the role of pollinating insects must be analyzed in the context of specific crop systems and varieties. Ideal pollinator management strategies should be tailored to the combination of crops and local pollinator species. However, it is important to note that the effect of pollination is not always linear to yield increases beyond a certain threshold; increases in pollinator visits or pollinator density only result in small marginal increases. This is due to the phenomenon of saturation, where flowers are almost entirely pollinated, so additional visits do not make much difference. The concept of “half-saturation rate” is used in pollination ecosystem models to estimate the point at which half of the potential yield has been achieved by the available pollinator population.

Understanding this saturation point is important so that pollinator intervention does not become futile or inefficient. Pollinator management strategies must consider the optimum efficiency point, not simply maximize the number of pollinators. In conclusion, the role of pollinating insects in food crop productivity includes increasing yield (quantity), improving product quality, and enhancing yield stability between years. These effects vary greatly between crop types, landscapes, and pollinator identities, and are influenced by landscape design and agricultural practices. In the context of sustainable agricultural systems, a deep understanding of the mechanisms, limits, and contextualization of pollination contributions is essential. Empirical research on a local tropical scale, especially in Indonesia, is needed to confirm the magnitude of these contributions to local food crops. These findings can then form the basis for practical recommendations to farmers to maximize productivity through pollinator population maintenance.

CONCLUSION

The diversity of pollinating insects has proven to be a key factor in supporting sustainable agricultural ecosystems. The diversity of pollinator species with complementary functions creates ecological stability, maintains pollination continuity throughout the season, and reduces the risk of production failure due to environmental disturbances. The presence of natural habitats and environmentally friendly land management practices further strengthen the existence of pollinators, so that the relationship between biodiversity conservation and agricultural productivity is balanced. On the other hand, the role of pollinating insects has a direct implication on increasing the quantity, quality, and stability of food crop yields. Empirical studies show that their contribution can increase yields by tens of percent, improve fruit quality, and reduce production variability between seasons. Therefore, efforts to protect and empower pollinators are not only relevant to ecosystem sustainability but also an important strategy in enhancing food security and the competitiveness of sustainable agriculture.

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