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Redesigning Pest Control: A Quantitative Review of Integrated Pest Management and Biocontrol for Sustainable Agriculture

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ABSTRACT: The continued reliance on chemical pesticides in global agriculture presents environmental, health, and economic challenges. This study evaluates the efficacy of Integrated Pest Management (IPM) and biocontrol strategies as sustainable alternatives. Drawing on secondary data from field trials and meta-analyses conducted in Sub-Saharan Africa and the U.S. Midwest, the analysis synthesizes quantitative outcomes related to pesticide reduction, crop yield, and ecosystem services. The methodology involved comparative analysis of intervention versus control outcomes, focusing on pest abundance, insecticide application rates, yield changes, and pollinator visitation. Results reveal that biocontrol interventions reduced pest abundance by 63% and increased yields by 43%, while IPM combined with ecosystem redesign cut insecticide use by 95% and boosted watermelon yields by 26–49%. Pollinator visitation also rose significantly, enhancing ecological resilience. The findings support the conclusion that ecologically integrated pest management strategies can reduce pesticide dependency without compromising, and often improving, agricultural productivity. These approaches are scalable when adapted to local agroecological conditions and supported by robust policy, education, and institutional frameworks.

Keywords: Integrated Pest Management, Biocontrol, Ecological Agriculture, Pesticide Reduction, Pollinator Services, Sustainable Farming, Agroecology.

INTRODUCTION

The persistent and widespread use of chemical pesticides in modern agriculture presents a complex challenge for sustainable food production. Over the past three decades, pesticide application trends have evolved in response to intensifying agricultural practices, policy changes, and heightened public awareness of their environmental and health implications. In 2023 alone, global pesticide use reached 3.73 million tons, underscoring the continuing reliance on chemical-based pest control systems. Although total usage has remained relatively stable, the intensity of pesticide application per hectare has increased, indicating deeper structural dependence. This intensification, especially pronounced in high-input agricultural regions such as Oceania (5.64 kg/ha), raises urgent questions about the long-term viability of such practices. In contrast, regions like Africa, with lower pesticide intensity (0.35 kg/ha), face different challenges, including limited access to effective pest management technologies (Midingoyi et al., 2018; Ofuya et al., 2023).

The urgency of this issue is further amplified by environmental and health risks associated with pesticide overuse. Pesticides contribute to the contamination of soils and water bodies, adversely impacting non-target organisms, including essential pollinators and aquatic life. Studies have identified significant ecological consequences, such as reductions in pest control efficacy due to agricultural landscape simplification (Rusch et al., 2016) and biodiversity loss caused by toxic residues (Schmidt-Jeffris et al., 2021). Furthermore, agricultural workers in developing and developed nations alike face heightened exposure risks, often without adequate protective measures or regulatory enforcement (Deguine et al., 2021; Rijal et al., 2018). As such, both ecological and human health considerations necessitate a critical evaluation of chemical pest control strategies.

To address these concerns, international organizations and agricultural institutions have increasingly endorsed sustainable pest management approaches. Prominent among these is Integrated Pest Management (IPM), a strategy promoted by the Food and Agriculture Organization (FAO) for balancing agricultural productivity with ecological integrity. IPM seeks to manage pest populations through a combination of biological, cultural, mechanical, and chemical tools that prioritize sustainability (Ewert et al., 2023). Evidence from regions implementing IPM indicates its success in reducing pesticide inputs while maintaining or even increasing crop yields (Raman et al., 2024; Tiwari, 2024). Supporting frameworks and guidelines have been developed to aid farmers in transitioning to these sustainable practices, helping mitigate risks associated with pesticide dependency (Costa et al., 2021).

The conceptual evolution of IPM is notable. Initially developed to suppress pest populations below economic thresholds, it has matured into a comprehensive strategy integrating ecological principles. It now encompasses tactics such as habitat manipulation and the conservation of beneficial organisms. As highlighted by Stenberg (2017), modern IPM emphasizes enhancing ecosystem services to achieve pest suppression naturally. The role of natural enemies predators, parasitoids, and pathogens in regulating pest populations has gained renewed attention, with several studies showing the efficacy of biocontrol agents in reducing pest prevalence without relying on synthetic chemicals (Jamian et al., 2016; Lommen et al., 2016). This transformation positions IPM as a keystone of agroecological transitions.

Biological control, a core component of IPM, is increasingly recognized for its potential to support sustainable agricultural systems. Unlike conventional methods that often require repeated chemical applications, biological control involves the deliberate use of natural enemies to manage pests, aligning with biodiversity conservation goals. Research underscores the effectiveness of such practices in improving ecological resilience and minimizing off-target impacts (Bielza et al., 2020; Panda et al., 2022). Studies demonstrate that biological control can be strategically integrated into IPM frameworks, delivering tangible benefits in both pest suppression and the promotion of ecosystem functions such as pollination (Leach et al., 2022).

Despite its promise, the uptake of IPM and biocontrol remains uneven across regions. While parts of Europe and North America have made strides in implementation, many developing countries continue to rely heavily on synthetic pesticides. Contributing factors include limited access to knowledge, training, and support structures necessary for transitioning to IPM. Moreover, the effectiveness of IPM varies with agroecological conditions, making localized research and adaptation essential. Nonetheless, global initiatives and research increasingly point to IPM and biocontrol as viable alternatives capable of reconciling agricultural productivity with sustainability.

Recent empirical evidence offers compelling insights into the performance of these interventions. For instance, biocontrol trials in Sub-Saharan Africa documented a 63% reduction in pest abundance, 50% decrease in crop damage, and a 43% yield increase, all without adverse effects on beneficial insect populations. Similarly, ecosystem redesigns integrated into IPM programs in the U.S. Midwest reduced insecticide use by 95% while increasing watermelon yield by 26% and pollinator visitation by 129% (Pecenka et al., 2021). On-farm validation trials of Integrated Pest and Pollinator Management (IPPM) reported 1–7 fewer pesticide applications and a 49% increase in marketable yield (Leach et al., 2022). These findings affirm the scalability and context-specific success of ecologically integrated pest management.

The present study builds upon this body of work by systematically evaluating quantitative impacts of IPM and biocontrol strategies using secondary data from recent trials and meta-analyses. Specifically, it explores how these interventions influence pesticide use, crop productivity, and ecosystem services across varied contexts. By doing so, it seeks to strengthen the empirical foundation for promoting sustainable pest management strategies at scale.

The novelty of this research lies in its comparative synthesis of quantitative outcomes across different IPM and biocontrol implementations. It highlights not only reductions in pesticide applications but also enhancements in yield and ecosystem functioning—outcomes critical for food security and environmental conservation. Furthermore, the study aims to identify enabling conditions for successful IPM adoption, including policy frameworks, farmer education, and ecological suitability. This approach offers actionable insights for stakeholders seeking to align agricultural practices with sustainability goals.

In scope, the paper integrates datasets from Sub-Saharan Africa and the U.S. Midwest, two contrasting agroecological zones. The former illustrates the potential of biocontrol under conditions of low pesticide access, while the latter demonstrates the viability of advanced ecosystem redesign under high-input systems. Together, these cases provide a robust basis for evaluating the adaptability and effectiveness of ecological pest management interventions.

In conclusion, the transition away from chemical-dependent agriculture is not only a matter of environmental necessity but also a practical opportunity. Integrated Pest Management and biological control provide scientifically validated tools to navigate this transition. As the global community seeks to balance productivity with ecological resilience, these strategies offer a credible and scalable path forward. This study contributes to this transition by synthesizing existing evidence and presenting a structured framework for assessing the impact and potential of IPM and biocontrol in sustainable agriculture.

METHOD

This study employs a structured synthesis of secondary data from published meta-analyses, field trials, and validation studies to assess the impact of Integrated Pest Management (IPM) and biological control strategies on pesticide use, crop yield, and ecological indicators. The methodology integrates diverse quantitative indicators and utilizes established frameworks for evaluating pesticide intensity and ecological impacts.

Metrics for Assessing Pesticide Use and Intensity

Evaluate trends and intervention impacts on pesticide application, this study applies several key metrics commonly used in agricultural assessments. These include:

- Pesticide Consumption (kg/ha/year): This measures the annual quantity of pesticides applied per hectare and serves as a primary indicator of chemical intensity in cropping systems. It captures changes over time and differences across regions and interventions (Kniss, 2017).
- Hazard Quotient: This composite measure incorporates both the quantity of pesticide used and its toxicity level, offering insights into the potential environmental and human health risks of chemical applications (Kniss, 2017).
- Active Ingredient (AI) Concentration: By quantifying the concentration of active substances in pesticide formulations, this metric supports a more granular understanding of chemical load on crops and ecosystems (Kniss, 2017).
- Risk Indicators: These include both qualitative and quantitative evaluations of risk posed to non-target organisms and ecological systems. Such indicators help monitor the broader consequences of pesticide reliance and promote the selection of lower-risk alternatives (Möhring et al., 2019).
- Coverage Area: This refers to the share of agricultural land receiving pesticide treatment relative to total cultivated area. It is critical for assessing spatial exposure and ecosystem vulnerability (Möhring et al., 2020).

These metrics provide a robust foundation for tracking pesticide intensity, identifying shifts resulting from IPM or biocontrol adoption, and informing sustainable policy design (Meena et al., 2020).

Defining and Measuring Ecological Indicators

Ecological performance indicators are central to evaluating the sustainability of pest management strategies. In this study, key indicators include:

- Pest Abundance: Typically measured through standardized sampling (e.g., sweep nets, sticky traps), pest abundance quantifies the density of target pest populations per unit area. These data help assess intervention efficacy in controlling pests while maintaining ecosystem stability (Herrera, 2018).

- Pollinator Visitation Rates: These are recorded through direct observation over fixed time intervals in designated plots. Pollinator counts per flower or per time unit provide a proxy for ecosystem service levels associated with biodiversity and crop productivity (Hyder et al., 2023).
- Functional Abundance Indices: These probabilistic metrics evaluate the contribution of pollinators to ecosystem functioning, allowing researchers to distinguish between mere presence and ecological effectiveness (Staton et al., 2021).
- Diversity Indices: Indices such as species richness and Shannon diversity are used to assess the biodiversity of pest and pollinator communities. These metrics illuminate the broader ecological consequences of pest control strategies (Parmentier et al., 2024).

These indicators facilitate a nuanced understanding of how ecological processes interact with pest management strategies, reinforcing the case for ecosystem-based approaches.

Evaluation of IPM and Biocontrol Trials

To determine the effectiveness of IPM and biocontrol interventions, this study synthesizes evidence from multiple types of research methodologies:

- Field Trials: Controlled field experiments provide real-world data on pest suppression, pesticide use, and yield impacts. Such trials are essential for validating the effectiveness of specific IPM techniques, including threshold-based spraying and habitat diversification (Pokharel et al., 2023).
- Meta-Analyses: Aggregated analyses of existing studies enhance statistical power and allow for broad generalizations about intervention efficacy across crops and contexts. This study draws heavily on meta-analyses for establishing baseline performance indicators (Delgado-Carrillo et al., 2024),
- Longitudinal Studies: Tracking variables over extended periods offers insights into the durability and sustainability of pest management effects. These studies are particularly relevant for observing ecological shifts that emerge gradually following IPM implementation (Dunn et al., 2020).
- Participatory Research: Engaging farmers directly in research design and implementation enables the development of locally adapted, socio-ecologically relevant IPM strategies. This method strengthens the practical relevance and adoption potential of interventions (Fountain, 2022).
- Ecological Modeling: Simulation models help project the interactions between pest populations, control agents, and environmental variables under different management regimes. These models are crucial for scenario analysis and long-term planning (Dainese et al., 2016).

By triangulating findings from these diverse methodologies, this study ensures a comprehensive understanding of intervention effectiveness and contextual applicability.

Data Sources and Inclusion Criteria

The study includes three primary datasets drawn from high-quality empirical sources:

- A meta-analysis of biocontrol interventions in Sub-Saharan Africa.
- A four-year field experiment integrating IPM and ecosystem redesign in the U.S. Midwest
- A two-year IPPM on-farm validation trial in commercial watermelon fields.

Inclusion criteria required quantitative reporting of pesticide use (in treatments or kg AI), yield outcomes (% change or ton/ha), and at least one ecological variable (e.g., pest or pollinator abundance). Studies were selected based on methodological rigor and relevance to the research objective.

Analytical Approach

Data were extracted and organized into comparative tables contrasting intervention and control groups. Key outcome variables were converted to percent change to facilitate cross-study comparison. Where appropriate, graphical representations (e.g., bar charts, scatter plots) were used to visualize trends and correlations, such as between pollinator visitation and yield.

The synthesis aims to identify consistent patterns in performance across IPM and biocontrol interventions, focusing on the dual goals of reducing pesticide reliance and enhancing agroecological outcomes. Results are contextualized within regional differences and implementation scales to assess transferability and policy implications.

RESULT AND DISCUSSION

This chapter presents the quantitative outcomes and qualitative insights derived from selected IPM and biocontrol interventions across three case contexts: biocontrol strategies in Sub-Saharan Africa, ecosystem-based IPM redesign in the U.S. Midwest, and IPPM validation trials in commercial watermelon production. These results collectively illuminate the agronomic, ecological, and adoption-related dimensions of sustainable pest management practices.

Biocontrol Interventions in Sub-Saharan Africa

Biocontrol efforts in Sub-Saharan Africa target various economically significant pests. Among the most common are Fall Armyworm (*Spodoptera frugiperda*) and Cotton Bollworm (*Helicoverpa armigera*), both of which cause extensive damage to maize and cotton crops respectively (Ratto et al., 2022). Other targeted pests include cabbage-damaging species like *Plutella xylostella* and aphids, especially in vegetable systems.

Quantitative assessments from meta-analyses demonstrate a 63% reduction in pest abundance, a 50% decrease in crop damage, and a 43% increase in yield. Notably, these interventions do not reduce the populations of beneficial organisms, such as pollinators and predators, provided they are well-designed and do not rely on broad-spectrum biocontrol agents (Tembo et al., 2018).

While concerns exist regarding non-target effects, especially in the absence of ecological knowledge, research shows that targeted, ecologically informed biocontrol methods can support biodiversity and improve overall agroecosystem functioning (Roesch-McNally et al., 2018).

Adoption progress remains mixed. While there is growing interest in biocontrol, actual implementation lags due to limited access to information and resources. Efforts to educate farmers and demonstrate biocontrol efficacy are essential for increasing adoption (Ratto et al., 2022; Tembo et al., 2018).

IPM + Ecosystem Redesign in the U.S. Midwest

A four-year field experiment incorporating IPM with ecosystem redesign was conducted on corn and watermelon crops across multiple U.S. Midwest locations. The design included flower strips, hedgerows, and diversified crop rotations techniques aimed at enhancing natural pest regulation and increasing habitat for pollinators and predators (Stiles et al., 2021; Tamburini et al., 2020).

The intervention reduced insecticide applications by 95%, from 97 to just 4 over the study period. Yield results showed no significant reduction in corn, while watermelon yield increased by 26% (Pecenka et al., 2021). Importantly, pollinator visitation rose by 129%, indicating enhanced ecosystem services alongside pest suppression.

These ecosystem-based approaches offer economic benefits over time by reducing reliance on chemical inputs, although initial investment in habitat infrastructure may be substantial. Long-term gains include improved biodiversity and reduced pest outbreaks.

Scalability remains a critical issue. While the intervention demonstrated success at experimental sites, wider adoption requires adapting methods to regional agricultural practices and economic contexts (Tamburini et al., 2020).

IPPM On-Farm Validation Trials

In 2020–2021, a validation study was conducted in commercial watermelon fields to assess the performance of Integrated Pest and Pollinator Management (IPPM) under real-world conditions. The trials involved reducing spray frequency using threshold-based application models.

Results showed that IPPM fields required 1–7 fewer insecticide applications compared to conventional standards. Yields improved by 49%, and pollinator visitation increased by 62% (Leach et al., 2022). These outcomes highlight the dual agronomic and ecological benefits of integrated strategies.

Farmer participation played a vital role in these results. Active involvement in planning and execution led to greater contextual relevance and improved compliance with IPM recommendations (Kamal et al., 2018).

However, discrepancies were noted between results in experimental and commercial settings. While experimental plots tended to produce more consistent yield improvements, commercial fields showed greater variability due to uncontrolled environmental and operational factors. These differences underscore the need for adaptive learning and flexibility in implementation (Leach et al., 2022).

Regarding statistical robustness, pollinator-related yield benefits are supported by extensive meta-analyses, though effect size may vary based on crop type, landscape complexity, and floral diversity (Kleijn et al., 2019).

Farmer perceptions significantly influence IPPM adoption. Many expressed initial concerns about implementation complexity and upfront costs. Nevertheless, when benefits such as reduced pesticide use and improved crop quality were explained, farmers reported increased willingness to adopt these practices (Fountain, 2022).

Summary of Key Quantitative Results

Table 1. Impact of IPM and Biocontrol Interventions

Intervention Type	Region & Crop Context	Pesticide Reduction	Yield Impact	Ecological Outcomes
Biocontrol	Sub-Saharan Africa	Not measured in kg AI	+43% yield	-63% pest abundance; -50% crop damage
IPM + ecosystem redesign	Midwest US (corn & watermelon)	-95% insecticide (97 to 4)	Watermelon: +26%; Corn: neutral	+129% pollinator visitation
IPPM validation (on-farm)	Midwest US (watermelon)	1–7 fewer applications	+49% marketable yield	+62% pollinator visitation

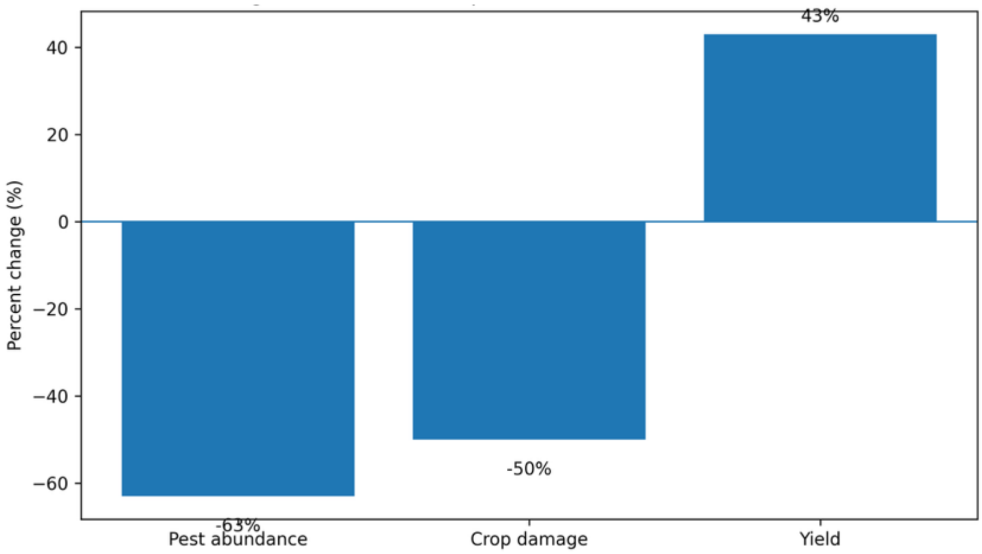

Figure 1. Biocontrol Impact Metrics (SSA)

Shows a 63% reduction in pest abundance, 50% decrease in crop damage, and 43% yield increase.

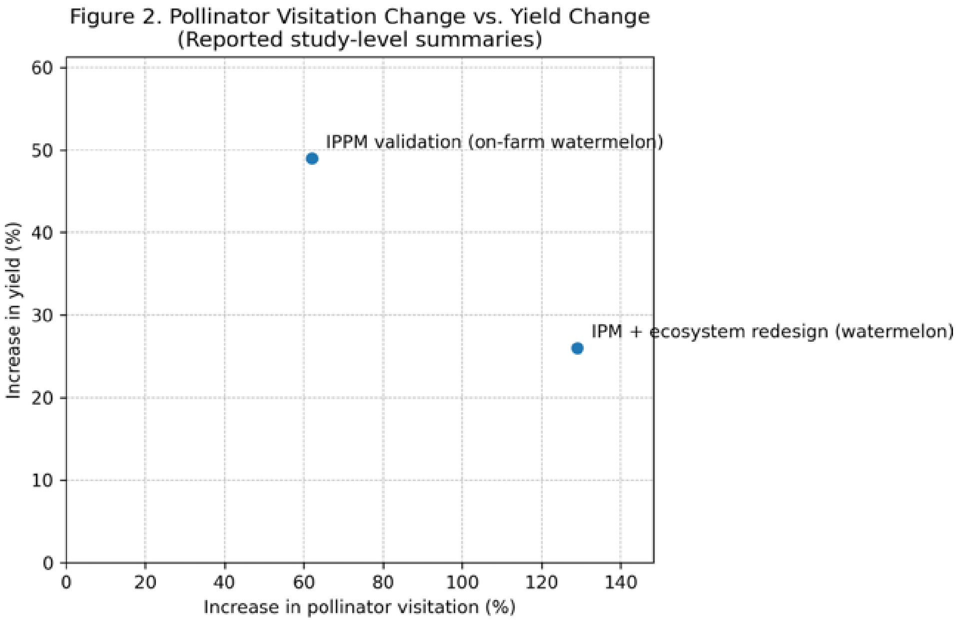

Figure 2. Pollinator Visitation vs. Yield Improvement

Scatter plot demonstrating a positive correlation between pollinator visits and crop yield improvements across IPPM and redesign trials.

These findings provide strong empirical support for ecologically integrated pest management strategies as viable alternatives to conventional pesticide-dependent models. The next chapter will discuss the broader implications, contextual challenges, and policy considerations emerging from these results.

The findings presented in this study affirm the efficacy of Integrated Pest Management (IPM) and biological control interventions in reducing pesticide reliance while enhancing crop productivity and ecosystem functioning. However, the effectiveness and scalability of these approaches vary across contexts. This discussion addresses the core factors influencing these variations, including methodological limitations in cross-context evaluations, institutional support mechanisms, agroecological factors, and systemic barriers to mainstreaming ecological pest management.

A key limitation in evaluating the comparative efficacy of IPM and biocontrol interventions lies in the heterogeneity of agricultural systems. Local farming cultures, economic structures, pest species composition, and environmental variables heavily influence how such interventions are implemented and their subsequent outcomes (Reganold & Wachter, 2016). For instance, strategies tailored for organic or diversified systems may not yield similar benefits in high-input monoculture settings. Similarly, pest species exhibit differential ecological responses to management; a pest well-regulated in one region may exhibit resistance or evade control in another due to varied life cycles or natural enemy dynamics (Pecenka et al., 2021). Such discrepancies complicate generalization.

Furthermore, the absence of standardized metrics across studies hinders synthesis. Evaluations may focus on yield, application frequency, pest abundance, or ecosystem services, often without alignment in data collection methods or reporting standards (Ewald et al., 2024). This inconsistency makes it difficult to benchmark success or establish universal best practices. External variables such as climate anomalies, emerging technologies, or market volatility also mediate outcomes, introducing further complexity to comparative analysis (Kleijn et al., 2019).

Institutional frameworks play a decisive role in supporting or impeding ecological pest management. Several countries have instituted policies aimed at reducing pesticide dependency. The European Union's Pesticide Directive 128/2009/EC, for example, promotes risk-based pesticide use and supports alternatives like IPM. Financial incentives, such as subsidies and ecological stewardship payments, have also proven effective in facilitating farmer adoption (Kleijn et al., 2019). Moreover, public and private investment in agricultural research helps generate knowledge on sustainable practices and disseminate innovations. Education and extension programs are equally vital, offering farmers the training needed to understand and apply complex ecological strategies (Wezel et al., 2020).

Agroecological variability significantly shapes the performance of IPM and biocontrol. Soil quality, microbial diversity, and baseline pest pressure determine how readily ecosystems respond to interventions. Richer biodiversity generally enhances system resilience, buffering against pest outbreaks (Aoujil et al., 2024). Climate factors such as temperature and precipitation also modulate pest dynamics and natural enemy effectiveness. For example, elevated temperatures may accelerate pest reproduction, undermining biological control success unless adaptive responses are incorporated (Nwadike et al., 2021).

Crop diversity and rotation patterns influence the functionality of natural pest regulation. Monocultures are more vulnerable to pest proliferation and often require more intensive interventions. Conversely, diverse cropping systems can suppress pest buildup and support beneficial species, thereby strengthening ecological control mechanisms (Negatu et al., 2016). Moreover, community engagement and localized knowledge are critical for tailoring interventions to specific environmental and socio-economic conditions. Participatory approaches enhance local relevance and encourage long-term commitment to sustainable practices (Nicholson et al., 2024).

Despite growing support, significant barriers limit the widespread adoption of ecological pest management. Economic constraints remain a major obstacle. Initial investments in infrastructure, such as flower strips or biocontrol agents, and the uncertainty of immediate returns can deter resource-constrained farmers (LaCanne & Lundgren, 2018). Without targeted subsidies or insurance mechanisms, ecological interventions may be viewed as risky. Additionally, many farmers lack awareness of IPM benefits or feel overwhelmed by its complexity. Educational gaps must be addressed to build confidence and capacity for ecological transition (Reganold & Wachter, 2016)(Rijal et al., 2018).

Institutional inertia within conventional systems also impedes change. Dependence on agrochemical supply chains and advisory services aligned with industrial models can discourage experimentation with alternative strategies. Farmers embedded in such networks may find limited incentives to deviate from established routines, especially when sustainable alternatives do not immediately improve yields or profit margins (Eyhorn et al., 2019). Regulatory ambiguities further complicate matters. In some contexts, policies unintentionally favor large-scale, chemically intensive systems through approval procedures, insurance structures, or market standards that marginalize diversified, low-input approaches (López-Antia et al., 2016).

In light of these findings, it is clear that ecological pest management strategies, while effective, are not universally applicable without adaptation. Policymakers, researchers, and practitioners must prioritize context-specific design, support mechanisms, and capacity-building efforts. Robust monitoring systems and standardized evaluation frameworks are needed to strengthen the evidence base and guide policy. By addressing economic, institutional, and ecological challenges simultaneously, the agricultural sector can more effectively transition toward sustainability.

CONCLUSION

This study evaluated the effectiveness of Integrated Pest Management (IPM) and biocontrol interventions across various agricultural contexts, focusing on their ability to reduce pesticide dependency while sustaining or enhancing crop productivity and ecological health. The analysis integrated empirical data from Sub-Saharan Africa and the U.S. Midwest, representing a spectrum of agroecological and socio-economic environments.

The results provide compelling evidence that ecologically-based pest management strategies can significantly reduce pesticide use. Biocontrol interventions in Sub-Saharan Africa led to a 63% reduction in pest abundance and a 50% decrease in crop damage, while improving yields by 43%. Similarly, the integration of ecosystem design principles within IPM frameworks in the U.S. Midwest achieved a 95% reduction in insecticide applications and a 26–49% increase in yield for watermelon crops, accompanied by a 62–129% rise in pollinator visitation. These outcomes demonstrate that ecological pest control can provide multifunctional benefits beyond pest suppression, including enhanced biodiversity and ecosystem service provision.

Furthermore, the study highlighted the crucial role of contextual adaptation in shaping the success of these interventions. Agroecological variables such as soil biodiversity, climate, and cropping systems influenced outcomes, emphasizing the need for locally tailored strategies. The importance of farmer participation and institutional support through training, policy incentives, and research was also underscored as vital for scaling up ecological approaches.

The primary scientific contribution of this study lies in its comparative synthesis of diverse intervention outcomes, showing that ecological pest management is not only feasible but also beneficial across varying scales and conditions. It reinforces the growing body of literature advocating for a transition away from chemically intensive agriculture toward more resilient, sustainable farming systems.

Looking forward, future research should focus on refining methodologies to measure ecological outcomes, standardizing impact assessment metrics, and exploring long-term economic and environmental trade-offs. Moreover, innovations in participatory research and agroecological modeling will be key to designing adaptive, scalable interventions.

In conclusion, the transition to sustainable agriculture is both necessary and achievable. IPM and biocontrol represent powerful tools in this transformation, capable of aligning agricultural productivity with ecological stewardship. With the right policy frameworks, capacity building, and localized adaptation, these strategies can help pave the way toward a more resilient and environmentally sound global food system.

REFERENCE

Aoujil, F., Litskas, V. D., Yahyaoui, H., Allaoui, N. E., Benbouazza, A., Aziz, A., Hafidi, M., & Habbadi, K. (2024). Sustainability Indicators for the Environmental Impact Assessment of Plant Protection Products Use in Moroccan Vineyards. *Horticulturae*, *10*(5), 473. https://doi.org/10.3390/horticulturae10050473

Bielza, P., Balanza, V., Cifuentes, D., & Mendoza, J. E. (2020). Challenges Facing Arthropod Biological Control: Identifying Traits for Genetic Improvement of Predators in Protected Crops. *Pest Management Science*, *76*(11), 3517–3526. https://doi.org/10.1002/ps.5857

Costa, D. M. D., Costa, J. M. D., Weerathunga, M. T., Prasannath, K., & Bulathsinhalage, V. N. (2021). Assessment of Management Practices, Awareness on Safe Use of Pesticides and Perception on Integrated Management of Pests and Diseases of Chilli and Tomato Grown by Small-Scale Farmers in Selected Districts of Sri Lanka. *Pest Management Science*, *77*(11), 5001–5020. https://doi.org/10.1002/ps.6542

Dainese, M., Montecchiari, S., Sitzia, T., Sigura, M., & Marini, L. (2016). High Cover of Hedgerows in the Landscape Supports Multiple Ecosystem Services in <scp>M</Scp>editerranean Cereal Fields. *Journal of Applied Ecology*, *54*(2), 380–388. https://doi.org/10.1111/1365-2664.12747

Deguine, J., Aubertot, J., Flor, R. J., Lescourret, F., Wyckhuys, K. A. G., & Ratnadass, A. (2021). Integrated Pest Management: Good Intentions, Hard Realities. A Review. *Agronomy for Sustainable Development*, *41*(3). https://doi.org/10.1007/s13593-021-00689-w

Delgado-Carrillo, O., Martén-Rodríguez, S., Ramírez-Mejía, D., Novais, S., Quevedo, A., Ghilardi, A., Sáyago, R., Lopezaraiza-Mikel, M., Pérez-Trujillo, E., & Quesada, M. (2024). Pollination Services to Crops of Watermelon (Citrullus Lanatus) and Green Tomato (Physalis Ixocarpa) in the Coastal Region of Jalisco, Mexico. *Plos One*, *19*(7), e0301402. https://doi.org/10.1371/journal.pone.0301402

Dunn, L., Támara, M. E. L., Reid, C. R., & Latty, T. (2020). Dual Ecosystem Services of Syrphid Flies (Diptera: Syrphidae): Pollinators and Biological Control Agents. *Pest Management Science*, *76*(6), 1973–1979. https://doi.org/10.1002/ps.5807

Ewald, J. A., Potts, G. R., Aebischer, N. J., Moreby, S. J., Wheatley, C. J., & Burrell, R. A. (2024). Fifty Years of Monitoring Changes in the Abundance of Invertebrates in the Cereal Ecosystem of the Sussex Downs, England. *Insect Conservation and Diversity*, *17*(5), 758–787. https://doi.org/10.1111/icad.12742

Ewert, F., Baatz, R., & Finger, R. (2023). Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption. *Annual Review of Resource Economics*, *15*(1), 351–381. https://doi.org/10.1146/annurev-resource-102422-090105

Eyhorn, F., Müller, A., Reganold, J. P., Frison, E., Herren, H. R., Luttikholt, L., Mueller, A., Sanders, J., Scialabba, N. E., Seufert, V., & Smith, P. (2019). Sustainability in Global Agriculture Driven by Organic Farming. *Nature Sustainability*, *2*(4), 253–255. https://doi.org/10.1038/s41893-019-0266-6

Fountain, M. T. (2022). Impacts of Wildflower Interventions on Beneficial Insects in Fruit Crops: A Review. *Insects*, *13*(3), 304. https://doi.org/10.3390/insects13030304

Herrera, C. M. (2018). Complex Long-Term Dynamics of Pollinator Abundance in Undisturbed Mediterranean Montane Habitats Over Two Decades. *Ecological Monographs*, *89*(1). https://doi.org/10.1002/ecm.1338

Hyder, M., Li, Y., Raza, M. F., Zhang, M., Chen, J., Mao, J., Bukero, A., & Zhang, L. (2023). Enhancing Coccinella Beetle Biological Pest Control via a Floral Approach in Cucumber Greenhouse. *Life*, *13*(10), 2080. https://doi.org/10.3390/life13102080

Jamian, S., Norhisham, A. R., Ghazali, A., Zakaria, A., & Azhar, B. (2016). Impacts of 2 Species of Predatory Reduviidae on Bagworms in Oil Palm Plantations. *Insect Science*, *24*(2), 285–294. https://doi.org/10.1111/1744-7917.12309

Kamal, M. M., Saleheen, K. M. N., Islam, Mst. S., & Ahmed, M. B. (2018). Adoption of Integrated Pest Management (IPM) Practices by the Vegetable Growers at Sadar Upazila Under Jhenaidah District. *Journal of the Bangladesh Agricultural University*, *16*(3), 366–371. https://doi.org/10.3329/jbau.v16i3.39394

Kleijn, D., Bommarco, R., Fijen, T. P. M., Garibaldi, L. A., Potts, S. G., & Putten, W. H. van der. (2019). Ecological Intensification: Bridging the Gap Between Science and Practice. *Trends in Ecology & Evolution*, *34*(2), 154–166. https://doi.org/10.1016/j.tree.2018.11.002

Kniss, A. R. (2017). Long-Term Trends in the Intensity and Relative Toxicity of Herbicide Use. *Nature Communications*, *8*(1). https://doi.org/10.1038/ncomms14865

LaCanne, C. E., & Lundgren, J. G. (2018). Regenerative Agriculture: Merging Farming and Natural Resource Conservation Profitably. *Peerj*, *6*, e4428. https://doi.org/10.7717/peerj.4428

Leach, A., Pecenka, J., & Kaplan, I. (2022). Does IPPM Bear Fruit? Evaluating Reduced-Risk Insecticide Programmes on Pests, Pollinators and Marketable Yield. *Journal of Applied Ecology*, *59*(12), 2993–3002. https://doi.org/10.1111/1365-2664.14294

Lommen, S. T. E., de Jong, P. W., & Pannebakker, B. A. (2016). It Is Time to Bridge the Gap Between Exploring and Exploiting: Prospects for Utilizing Intraspecific Genetic Variation to Optimize Arthropods for Augmentative Pest Control – A Review. *Entomologia Experimentalis et Applicata*, *162*(2), 108–123. https://doi.org/10.1111/eea.12510

López‐Antia, A., Feliú, J., Camarero, P. R., Ortiz‐Santaliestra, M. E., & Mateo, R. (2016). Risk Assessment of Pesticide Seed Treatment for Farmland Birds Using Refined Field Data. *Journal of Applied Ecology*, *53*(5), 1373–1381. https://doi.org/10.1111/1365-2664.12668

Meena, R. S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnický, M., Sharma, M. P., Yadav, G. S., Jhariya, M. K., Jangir, C. K., Pathan, S. I., Dokulilová, T., Pecina, V., & Marfo, T. D. (2020). Impact of Agrochemicals on Soil Microbiota and Management: A Review. *Land*, *9*(2), 34. https://doi.org/10.3390/land9020034

Midingoyi, S.-K., Kassie, M., Muriithi, B., Diiro, G., & Ekesi, S. (2018). Do Farmers and the Environment Benefit From Adopting Integrated Pest Management Practices? Evidence From Kenya. *Journal of Agricultural Economics*, *70*(2), 452–470. https://doi.org/10.1111/1477-9552.12306

Möhring, N., Bozzola, M., Hirsch, S., & Finger, R. (2020). Are Pesticides Risk Decreasing? The Relevance of Pesticide Indicator Choice in Empirical Analysis. *Agricultural Economics*, *51*(3), 429–444. https://doi.org/10.1111/agec.12563

Möhring, N., Gaba, S., & Finger, R. (2019). Quantity Based Indicators Fail to Identify Extreme Pesticide Risks. *The Science of the Total Environment*, *646*, 503–523. https://doi.org/10.1016/j.scitotenv.2018.07.287

Negatu, B., Kromhout, H., Mekonnen, Y., & Vermeulen, R. (2016). Use of Chemical Pesticides in Ethiopia: A Cross-Sectional Comparative Study on Knowledge, Attitude and Practice of Farmers and Farm Workers in Three Farming Systems. *The Annals of Occupational Hygiene*, *60*(5), 551–566. https://doi.org/10.1093/annhyg/mew004

Nicholson, C., Lonsdorf, E. V, Andersson, G. K., Knapp, J., Svensson, G. P., Gönczi, M., Jonsson, O., Miranda, J. R. d., Williams, N. M., & Rundlöf, M. (2024). Landscapes of Risk: A Comparative Analysis of Landscape Metrics for the Ecotoxicological Assessment of Pesticide Risk to Bees. *Journal of Applied Ecology*, *61*(5), 975–986. https://doi.org/10.1111/1365-2664.14622

Nwadike, C., Joshua, V. I., Doka, P. J. S., Ajaj, R., Hashidu, U. A., Gwary-Moda, S., Danjin, M., & Moda, H. M. (2021). Occupational Safety Knowledge, Attitude, and Practice Among Farmers in Northern Nigeria During Pesticide Application—A Case Study. *Sustainability*, *13*(18), 10107. https://doi.org/10.3390/su131810107

Ofuya, T. I., Okunlola, A. I., & Mbata, G. N. (2023). A Review of Insect Pest Management in Vegetable Crop Production in Nigeria. *Insects*, *14*(2), 111. https://doi.org/10.3390/insects14020111

Panda, S., Sharma, A., & Tyagi, S. (2022). Integrated Pest Management Technology as a Means to Cost Efficiency for Cotton Crop in Rajasthan, India. *Asian Journal of Agricultural Extension Economics & Sociology*, 53–63. https://doi.org/10.9734/ajaees/2022/v40i930975

Parmentier, L., Vanderstappen, H., & Haesaert, G. (2024). Biodiverse Management of Perennial Flower Margins in Farmland: Meandering Mowing by "Three-Strip Management" to Boost Pollinators and Beneficial Insects. *Insects*, *15*(12), 953. https://doi.org/10.3390/insects15120953

Pecenka, J., Ingwell, L. L., Foster, R. E., Krupke, C. H., & Kaplan, I. (2021). IPM Reduces Insecticide Applications by 95% While Maintaining or Enhancing Crop Yields Through Wild Pollinator Conservation. *Proceedings of the National Academy of Sciences*, *118*(44). https://doi.org/10.1073/pnas.2108429118

Pokharel, S. S., Han, Y., Fang, W., Parajulee, M. N., & Chen, F. (2023). Intercropping Cover Crops for a Vital Ecosystem Service: A Review of the Biocontrol of Insect Pests in Tea Agroecosystems. *Plants*, *12*(12), 2361. https://doi.org/10.3390/plants12122361

Raman, R. S., Srilekha, G., B., S. K., Singh, N., Chandra, P. K., & Jabbar, A. S. A. A.-Z. (2024). Enhancing Cucumber Production Sustainability by Incorporated Pest Management: A Comparative Evaluation of Cost and Profitability. *E3S Web of Conferences*, *552*, 1055. https://doi.org/10.1051/e3sconf/202455201055

Ratto, F., Bruce, T. J. A., Chipabika, G., Mwamakamba, S., Mkandawire, R., Khan, Z. R., Mkindi, A. G., Pittchar, J., Chidawanyika, F., Sallu, S. M., Whitfield, S., Wilson, K., & Sait, S. M. (2022). Biological Control Interventions and Botanical Pesticides for Insect Pests of Crops in Sub-Saharan Africa: A Mapping Review. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.883975

Reganold, J. P., & Wachter, J. M. (2016). Organic Agriculture in the Twenty-First Century. *Nature Plants*, *2*(2). https://doi.org/10.1038/nplants.2015.221

Rijal, J., Regmi, R., Ghimire, R., Puri, K. D., Gyawaly, S., & Poudel, S. (2018). Farmers' Knowledge on Pesticide Safety and Pest Management Practices: A Case Study of Vegetable Growers in Chitwan, Nepal. *Agriculture*, *8*(1), 16. https://doi.org/10.3390/agriculture8010016

Roesch-McNally, G., Arbuckle, J. G., & Tyndall, J. (2018). Barriers to Implementing Climate Resilient Agricultural Strategies: The Case of Crop Diversification in the U.S. Corn Belt. *Global Environmental Change*, *48*, 206–215. https://doi.org/10.1016/j.gloenvcha.2017.12.002

Rusch, A., Chaplin-Kramer, R., Gardiner, M. M., Hawro, V., Holland, J. M., Landis, D. A., Thies, C., Tscharntke, T., Weisser, W. W., Winqvist, C., Woltz, M., & Bommarco, R. (2016). Agricultural Landscape Simplification Reduces Natural Pest Control: A Quantitative Synthesis. *Agriculture Ecosystems & Environment*, *221*, 198–204. https://doi.org/10.1016/j.agee.2016.01.039

Schmidt-Jeffris, R. A., Beers, E. H., & Sater, C. (2021). Meta-Analysis and Review of Pesticide Non-Target Effects on Phytoseiids, Key Biological Control Agents. *Pest Management Science*, *77*(11), 4848–4862. https://doi.org/10.1002/ps.6531

Staton, T., Walters, R. J., Smith, J., Breeze, T. D., & Girling, R. D. (2021). Management to Promote Flowering Understoreys Benefits Natural Enemy Diversity, Aphid Suppression and Income in an Agroforestry System. *Agronomy*, *11*(4), 651. https://doi.org/10.3390/agronomy11040651

Stenberg, J. A. (2017). A Conceptual Framework for Integrated Pest Management. *Trends in Plant Science*, *22*(9), 759–769. https://doi.org/10.1016/j.tplants.2017.06.010

Stiles, S., Lundgren, J. G., Fenster, C. B., & Nottebrock, H. (2021). Maximizing Ecosystem Services to the Oil Crop <i>Brassica Carinata</I> Through Landscape Heterogeneity and Arthropod Diversity. *Ecosphere*, *12*(7). https://doi.org/10.1002/ecs2.3624

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Heijden, M. G. A. van der, Liebman, M., & Hallin, S. (2020). Agricultural Diversification Promotes Multiple Ecosystem Services Without Compromising Yield. *Science Advances*, *6*(45). https://doi.org/10.1126/sciadv.aba1715

Tembo, Y., Mkindi, A. G., Mkenda, P. A., Mpumi, N., Mwanauta, R. W., Stevenson, P. C., Ndakidemi, P. A., & Belmain, S. R. (2018). Pesticidal Plant Extracts Improve Yield and Reduce Insect Pests on Legume Crops Without Harming Beneficial Arthropods. *Frontiers in Plant Science*, *9*. https://doi.org/10.3389/fpls.2018.01425

Tiwari, A. K. (2024). IPM Essentials: Combining Biology, Ecology, and Agriculture for Sustainable Pest Control. *Journal of Advances in Biology & Biotechnology*, *27*(2), 39–47. https://doi.org/10.9734/jabb/2024/v27i2697

Wezel, A., Herren, B., Kerr, R. B., Barrios, E., Gonçalves, A. L., & Sinclair, F. (2020). Agroecological Principles and Elements and Their Implications for Transitioning to Sustainable Food Systems. A Review. *Agronomy for Sustainable Development*, *40*(6). https://doi.org/10.1007/s13593-020-00646-z