



Integrated Pest Management as a Sustainable Strategy for Reducing Chemical Dependency and Enhancing Productivity in Modern

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Abstract: Integrated Pest Management (IPM) is an important alternative to conventional agriculture relying on chemical inputs and is applicable to many aspects of the ecosystems, economy, and productivity, but there is not enough quantification when considering the overall effectiveness. The experimental study was conducted in 20 agricultural research farms in various agroecological zones with Randomized Complete Block Design (RCBD) with 320 replicated experimental plots over 2 consecutive cropping seasons. Biological control agents, crop rotation, resistant varieties, pheromone traps, mechanical weed control, cultural practices, botanical pesticides, selective chemicals, and an IPM package were evaluated as strategies. Pest monitoring was done weekly, crop growth parameters and economic parameters were measured, and statistical analyses were done by ANOVA, multiple linear regression, and principal component analysis. Our results show that overall implementation of IPM resulted in a 46.8% reduction in chemical pesticide used, a 35.2% reduction in pest infestation, and a 24.7% increase in beneficial insects. The yield under conventional management was 19.8% higher, and the net economic return was 21.5% higher. Biological control efficiency ($\beta = 0.47$, $p < 0.001$) and pest monitoring frequency ($\beta = 0.40$, $p < 0.001$) were the most important factors for pest suppression, and the model accounted for 75.6% of the variance. Three components were also found by PCA that explained 82.9% of total variance: biological pest control, crop productivity, and economic returns. This work brings a novelty in the quantification of the multiple benefits that IPM offers, combining pest suppression, environmental sustainability, and economic viability. The findings are evident that IPM is an effective method that can reduce the use of chemicals in agriculture and ensure agricultural productivity and a healthy environment in modern agriculture.

Keywords: Integrated Pest Management, Sustainable Agriculture, Chemical Dependency Reduction, Crop Productivity, Eco-Friendly Pest Control

Introduction

The challenge of the twenty-first century of agriculture is to have sufficient food available in the world to feed the growing population without causing harm to the environment through intensive production methods. Traditional pest control has been practiced for years and years, which has improved yields but has also had a significant impact on the environment, including pest resistance, a decrease in beneficial insects, and contamination of soil and water resources (Barzman et al., 2015). Agroecology is a model of rethinking and bettering ecological and social justice in agriculture and is centered around the principles of biodiversity, soil health, and natural regulation (Hawes et al., 2021). One of the most promising concepts within this paradigm is Integrated Pest Management (IPM), which seeks to reduce the use of synthetic pesticides through an integrated management of various other pest management techniques like biological, cultural, mechanical, and chemical (Pretty & Bharucha, 2015).

The principles of IPM have been outlined in the ecological literature. Pest control in agroecosystems can be considered as an ecological problem because pest population dynamics is dependent on the complicated relationship between the crop, natural enemies, and environmental factors (Ekström & Ekbom, 2011). The eight principles of IPM by Barzman et al. (Barzman et al., 2015) offer a structured approach to the implementation of this ecological approach, such as prevention and suppression, monitoring, decision-making based on thresholds, and integration of non-chemical methods. While these principles are known, there is a lack of evidence of the success of IPM in suppressing pests, boosting yields, enhancing environmental health and sustainability, and delivering economic returns, especially in varying contexts. Several studies have been conducted on different aspects of IPM, such as the compatibility of insecticides with natural enemies (Yarahmadi & Rajabpour, 2024) or on IPM in a certain crop system but without the comprehensive assessment of IPM impact on the entire system (Dhawan & Peshin, 2009).

The uniqueness of this work is that it integrates the various components of agricultural performance in which IPM can be useful and quantifies them. Previous studies have demonstrated the potential of IPM to minimize pesticide application (Ediagbonya et al., 2025) or improve crop yields (Fahad, 2023), but there are a limited number of studies that have evaluated IPM in one experimental design to include pest control, environmental sustainability, and economic viability. In addition, advanced statistical techniques such as multiple linear regression and principal component analysis can be used to determine the most significant factors of IPM and underlying relationships between IPM key factors. This study's results are of direct relevance for the design of sustainable agricultural systems that are able to lower chemical dependency without compromising productivity and profitability, which will help to resolve critical issues of food safety, environmental contamination, and long-term agroecosystem resilience (Shah & Razaq, 2021).

Section 2 provides a literature review of the principles, practices, and outcomes of IPM, which is the context of the present study in the field of sustainable agriculture research. In section 3, the experimental design and data collection methods employed in the current study are

presented, as well as the statistical analyses performed. The outcome of field experiments (impact of IPM on pest population, yield of the crop, and economic returns) is shown in Section 4. The implications for agricultural policy and practice are discussed in Section 5, and the contributions and directions for future research are summarized in Section 6.

Literature Review

The IPM concept was an expression of the shift from the reductionist approach in agriculture science to the ecological approach that considers systems thinking and is applied in agriculture. IPM programs were initially created in the 1950s and 1960s after reports of pesticide resistance and secondary pest issues began to appear as well as pesticide residues in the environment due to the use of synthetic insecticides (Barzman et al., 2015). IPM is based on the principle of using multiple control techniques to achieve pest control; chemicals last on the list of control techniques if they are needed. This principle has been translated into an operational strategy of eight guidelines that emphasize avoidance of problem escalation, monitoring, decision-making using thresholds, and a combination of biological, cultural, physical, and chemical approaches (Barzman et al., 2015). While these principles have been adopted by the national agricultural extension services and international development organizations, there have been some variations in how they are actually applied in practice, and farmers still use high volumes of chemical pesticides (Pretty & Bharucha, 2015).

The science literature contains information on ecological principles of IPM. Pest control in agro-ecosystems is primarily an ecological process, and the level or density of pest species is affected by multiple complex interactions between the crop, natural enemies, and environmental conditions (Ekström & Ekbom, 2011). The use of natural enemies like pathogens, parasitoids, and predators to suppress pest populations is one of the most important components of IPM, and it is proven to be effective and sustainable pest control in many cropping systems (Yarahmadi & Rajabpour, 2024). However, biological control might be negatively affected because of the killing of pests' natural enemies with the use of broad-spectrum insecticides, which ultimately results in the feedback of the dependability of insecticides (Yarahmadi & Rajabpour, 2024). This observation underlines the need for a selective use of pesticides and for combining chemical and biological techniques in a way that maintains the agro-ecosystems' functional integrity.

There are a number of other methods of pest suppression, including cultural and mechanical controls, that can reduce the need for other control applications. Crop rotation, for example, will help disrupt the life cycles of soil-borne pests and disease, as they will not have their host crop plants, and resistant crop varieties will make the crop less susceptible to pests and disease. (Dhawan & Peshin, 2009). In addition to chemical control of pest population, mechanical control measures such as sticky and pheromone traps for monitoring and direct control of pest population can be utilized, especially in organic or low-input farming systems (Fahad, 2023). As part of an IPM strategy, these have been shown to reduce the use of pesticides by 30-50% in a range of crops and can maintain or increase yield (Ediagbonya et al., 2025). But the feasibility of IPM is questionable, as some studies indicate that an IPM may lead to an increase in labor cost and complexity of management as compared to pesticide application, leading to a

decrease in the benefit of reduced pesticide applications (Shah & Razaq, 2021). There is a lot of empirical evidence for the effectiveness of IPM, from a diverse array of research across a variety of agro-ecological zones and cropping systems. IPM has been shown to reduce pesticide usage by 40-60% and increase yields by 10-20% and has been successfully demonstrated in Asia and Africa to reduce pesticide use, particularly in smallholder farming systems where pesticide overuse is common (Pretty & Bharucha, 2015). Also, IPM has been proved to be a strategy that reduces the environmental impact of agriculture by reducing pesticide usage, and beneficial insects and soil overall health is enhanced in temperate regions (Kaur & Kaur, 2020). Most of these studies, however, have limited themselves to a single IPM component or to a particular crop system, and it is difficult to extrapolate from them to other systems. Besides, few experiments have been designed to quantify the effect of IPM on the control of different pests, on the productivity of the crop, and on the sustainability and return on investment on a single experiment, thus making it difficult to understand the trade-offs and synergies in these dimensions.

The present study, therefore, was oriented to filling this gap by making a multi-site assessment of IPM involving the use of biological, cultural, mechanical, and chemical control strategies in a comprehensive experiment. Instead of studying each component of IPM individually as in previous studies, this study tests the synergy of a complete package of IPM under a variety of agro-ecological conditions and employs sophisticated statistical tools to determine which predictors are most important for pest suppression and to elucidate the structure of the relationships between key variables. The novelty of the work is that it brings together the simultaneous advantages of IPM (pest suppression, environmental sustainability, and economic viability) and gives a scientific foundation to turn away from the conventional agricultural system with pesticides toward more ecologically balanced IPM strategies.

Materials and Methods

Experimental Design and Study Sites

We employed a field-based experimental research design to evaluate the effectiveness of Integrated Pest Management (IPM) approaches in reducing chemical pesticide dependency while maintaining crop productivity and environmental sustainability. The study was conducted at 20 agricultural research farms distributed across diverse agroecological zones to ensure the generalizability of the findings. A total of 320 experimental plots were established using a Randomized Complete Block Design (RCBD) with four treatment groups and three replications over two consecutive cropping seasons. The RCBD was selected to control for spatial heterogeneity within each farm, as blocks were defined based on soil type, topography, and previous crop history, thereby reducing the error variance associated with environmental gradients.

Each experimental plot measured 10 m × 10 m, with a 2 m buffer zone between adjacent plots to minimize edge effects and treatment interference. The four treatment groups consisted of: (1) a comprehensive IPM package incorporating all evaluated strategies; (2) biological control agents combined with cultural practices; (3) mechanical methods and botanical pesticides; and (4) a conventional pesticide-based management system serving as the control. The allocation

of treatments to plots within each block was randomized using a computer-generated random number sequence, ensuring that each treatment had an equal probability of being assigned to any given plot.

Treatment Implementation

Biological, cultural, mechanical, and chemical pest management strategies were evaluated. Biological control agents consisted of predatory insects. *Chrysoperla carnea* and *Coccinella septempunctata* and the use of entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*) at rates of 1×10^8 conidia/ha. Crop rotation with non-host species, intercropping with repellent crops (such as marigold and basil), and a variety of resistant crop varieties that had been previously tested for resistance to major pest species were used as cultural practices. Mechanical control was performed by regular hoeing and mulching to control weeds, and the use of 5 pheromone traps and 10 yellow and blue sticky traps per hectare for monitoring and mass trapping.

Neem oil (*Azadirachta indica*) at 2% concentration and garlic extract at 5% concentration were sprayed weekly when pests were seen above the economic threshold. Only if the pest levels were deemed to be critical, and non-mechanized controls were not considered to be effective. The use of chemical pesticides was considered, and only pesticides with low toxicity to non-target organisms (e.g., spinosad and chlorantraniliprole) were used. All of these strategies were incorporated into the comprehensive IPM package, working together in a coordinated fashion and making decisions based on weekly pest monitoring data and economic threshold levels.

Data Collection and Measured Variables

The two cropping seasons were sampled for field observations and laboratory analyses. The pest populations were monitored weekly, following standard sampling procedures, such as visual inspection of 20 plants sampled at random in each plot, sweep net sampling (20 sweeps per plot), and pheromone trap counts. Samples were taken along the same methods, and the number of beneficial insects recorded by the species, using taxonomic keys. The incidence of disease was determined as the percentage of plants showing symptoms of the major fungal and bacterial diseases and was observed weekly.

Three growth stages of the crop were judged to be important for growth and were measured (vegetative, flowering, and grain filling). The height of the plants was determined from soil surface to the top of the main stem with measuring tape. LAI was derived from the diffuse light measurement with the use of a portable plant canopy analyzer (LI-COR Biosciences, Lincoln, NE, USA) with the name of LAI-2200C. The chlorophyll content was measured with a SPAD-502 Plus chlorophyll meter (Konica Minolta, Tokyo, Japan) from the uppermost fully expanded leaf of 10 randomly selected plants in each of the 10 plots. The plot area was fully harvested at harvest time, threshed, and the grain was dried to 14% moisture and weighed at harvest.

Reported pesticide use was the amount of pesticide active ingredient applied per season per hectare (liters/ha). Biological control efficiency was determined as the percentage decrease in pest density for the biological control treatments as compared to the untreated control. The triphenyltetrazolium chloride (TTC) reduction method was used to determine soil microbial

activity, based on the activity of dehydrogenase enzymes, at the start and end of each cropping season from 0 to 15 cm soil depth. The cost of seed, fertilizers, pesticides, labor, and machines was noted for each treatment, and the net economic return = gross revenue - total production cost.

Data Preprocessing and Quality Control

Collected data were carefully preprocessed to assure data quality and statistical validity. Plots where more than 20% of the data were missing for any measured variable were not included in the data. The values of the remaining missing observations were imputed by k-nearest neighbors ($k = 5$) and Euclidean distance as the distance metric. Potential measurement errors (defined as less than $Q1 - 1.5 \times IQR$ or more than $Q3 + 1.5 \times IQR$) were manually inspected and later replaced by the median that was calculated for the treatment group on that variable.

All the variables were normalized using the min-max normalization method between 0 and 1, so that those on the different scales have matchable measurements. Laboratory quality control included the following: use of certified reference materials, duplicated analyses (10%), and inter-laboratory proficiency testing programs. The normality of the data distribution was checked using the Shapiro-Wilk test, and homogeneity of variances was checked using Levene's test. Logarithmic or square root transformations were used where appropriate if variables were not normally distributed.

Statistical Analysis

All of the measured variables were analyzed for treatment groups and cropping seasons, and descriptive statistics such as means, standard deviation, and coefficient of variation were generated for all of the variables. T-tests were conducted to test for differences among change scores of the measured variables, whereas one-way analysis of variance (ANOVA) was used to test for differences among treatment means for each of the measured variables, followed by Tukey's Honestly Significant Difference (HSD) test for all pairwise comparisons for which the F-test was significant. The key outcome variables were analyzed by two-way ANOVAs (season and treatment as fixed factors and block as a random factor) to examine the interactions between treatment and season.

The bivariate relationships for all variables measured were investigated using Pearson correlation analysis, which categorizes the correlation as weak when $|r| < 0.3$, moderate when $0.3 \leq |r| < 0.7$, and strong when $|r| \geq 0.7$. Multiple linear regression analysis identified the most important of these main rules affecting pest suppression efficiency: biological control efficiency, pest monitoring frequency, resistant crop, and number of cultivars.

To find that the measured variables were related to each other in some ways, and to reduce the dimensionality of the data, Principal Component Analysis (PCA) was performed. For determining the number of principal components, the Kaiser criterion (eigenvalue > 1) was employed as well as the scree plot. The varimax rotation was employed to further "interpretability" component loadings, and loadings above 0.4 (absolute value) were deemed as significant. All statistical analysis was done using R (version 4.3), SPSS 29, SAS 9.4, ArcGIS Pro, and data management in Microsoft Excel.

Results

This large field trial provides substantial data on the diverse benefits of integrated pest management, ecological, agronomic, and economic. To evaluate the impact of IPM on pest suppression, biodiversity, and crop performance, 320 experimental plots were evaluated during two seasons, followed by an examination of the importance of predictability and the structure of a successful pest management. The findings are shown in two subsections: one showing the general success of IPM as compared to conventional management and the other showing the multivariate analysis to find the most important factors that influenced the outcome.

Impact of IPM on Pest Suppression, Biodiversity, and Crop Performance

IPM had the greatest influence on decreasing the use of chemical pesticides. Overall, IPM practices resulted in a 46.8% decrease in the amount of chemical pesticides used (on a total volume of active ingredient/ha/season basis) compared to the conventional system of management. The substantial decrease in pesticide use was accompanied by a 35.2% decrease in pest infestation, proving that the exclusive alternative control measures implemented in the IPM system were very effective at controlling pests. In addition to the decrease in pest pressure, the incidence of crop diseases also decreased by 18.9%, demonstrating that the integrated approach also reduced the incidence of secondary disease outbreaks, which frequently are compounded by feeding activity of pests.

This ecological element of IPM was not just about pest control but also part of the IPM plan was the conservation and enhancement of beneficial insect populations. Numbers of beneficial insects (predators and parasitoids) were 24.7% greater in the IPM plots than in conventional plots. This increase likely stems from decreasing the use of "dirty" pesticides with harmful effects on non-target organisms and the intentional use of biological control organisms in the IPM package. Increased abundance of beneficial insects is important to consider when looking at the health of agroecosystems, because beneficial insects provide key services to the agroecosystems, such as natural pest management and pollination. Also, 13.2% greater soil dehydrogenase activities in the IPM plots show improvements in soil biological fertility and nutrient cycling capacity. Improving soil health is a process that takes time to achieve, and a principle of reduced chemical use is that soil organisms are critical to decomposing organic material, mineralizing nutrients, and growing plants.

The agronomic and economical results also were very good. Results indicated that there was a higher productivity in the IPM-treated plots than the conventional management (19.8% surpassing the latter), proving that the application of lower amounts of chemical pesticides had no effect but rather contributed to a better productivity of the crop. Increases in crop productivity due to this increased yield have been linked to decreased damage from pests, enhanced plant health, and increased soil fertility. The efficiency of the IPM approach over conventional management was seen to have a density reduction in pest population by 37.4% under the IPM approach, whereas the density reduction achieved by the conventional approach was not apparent at all. Environmental sustainability of the system (composite index incorporating all three variables—pesticides, beneficial insects, and soil health) was achieved with a 28.3% increase in the IPM plots. Finally, the net economic return (gross return - total

production costs) was 21.5% higher with IPM, thus demonstrating that it is not only the more environmentally friendly method but also the more economical one for the grower. These results all collectively demonstrate the “win-win” effect of IPM with respect to all crucial components of agricultural performance and its contribution to disassociating agricultural productivity from chemical pesticides.

Predictors of Pest Management Success and Multivariate Analysis

Biological control efficiency was the most important predictor of the success of pest suppression, with a standardized regression coefficient of $\beta=0.47$ ($p<0.001$) in the regression analysis. Preservation of and enhancement of beneficial organisms plays an important role in IPM systems, in accordance with ecological principles (Ekström & Ekbom, 2011), and natural enemies are important mediators of pest control in IPM systems. The second most important predictor was regular and systematic monitoring to allow informed decisions to be made on pest management ($\beta=0.40$, $P<0.001$). This scenario aligns with the basic tenet of IPM, which uses monitoring to find the pest levels at or above ETL and to decide when action will be needed to lower pest levels (Barzman et al., 2015). Host plant resistance was another significant predictor ($\beta=0.34$, $p<0.001$), and it has been clearly established to be the first line of defense against pests and reduce the need for other control measures (Dhawan & Peshin, 2009). Similarly, crop rotation and intercropping, a part of cultural control, were fourth important ($\beta=0.29$, $p=0.002$), which means adoption of this preventive measure is also important in general pest management. The overall model of the full regression model provided an R^2 of 0.756, indicating that these four predictors in combination accounted for 75.6% of the variation in efficiency of pest suppression in the experiment plots.

The interrelationship of the key variables was further analyzed by means of Pearson correlation analysis. There was a positive relationship between the IPM index (composite index of the intensity of IPM practices) and the productivity of crops ($r = 0.82$, $p < 0.001$). There was a favorable and significant correlation between biological control efficiency and abundance of beneficial insects ($r = 0.80$ and $p < 0.001$), indicating the importance of natural enemies to make the biological control an effective procedure. The use of pesticides, on the other hand, was highly negatively correlated with biological control efficiency ($r=-0.78$, $p<0.001$), indicating that the more biological control was used, the less pesticide was used. Similarities between the correlation patterns described can be found in the ecological trade-offs linked to managing pests, as they can result in disturbance of biological control services as part of pesticide use as a broad-spectrum approach (Yarahmadi & Rajabpour, 2024).

Principal Component Analysis (PCA) was applied to simplify the data to identify the structure behind the number of observed variables, which was actually hidden. Three main components were selected (eigenvalue > 1), accounting for 82.9% of the total variance of the data. The first principal component (PC1) accounted for 39.8% of the variance and was defined by high scores of biological control efficiency, abundance of beneficial insects, and pest suppression efficiency; and was thought to be related to biological pest control and biological pest suppression. The second principal component (PC2), explaining 26.9% of the variation, was defined by crop yield, leaf area index, and environmental sustainability index, which indicated

crop productivity and environmental sustainability. The third principal component (PC3) with a variance of 16.2% is highly correlated to the net economic return and chemical pesticide reduction index that corresponds to the economic returns and lesser dependence on chemical pesticides. The relative separation of these three aspects implies that the benefits of IPM are multifaceted and that the benefits gained are the suppression of pests, increased productivity, and increased economic viability, which are approximately separable benefits that can be improved simultaneously in IPM. In addition to providing a shortcut description of the complex interactions within the ecological, agronomic, and economic components of an IPM system, it serves to reinforce the concept that IPM is an integrated approach that provides synergistic effects on multiple aspects of agricultural performance.

Discussion

The results of this study have important meaning in both theoretical knowledge of sustainable pest management and the actual use of IPM in an agricultural system. Theoretically, the ability to discriminate between highly efficient (versus less efficient or ineffective) biological control and desired pest monitoring frequency as the strongest predictors of success in pest suppression provides reinforcement for the ecological foundations of IPM that biological regulation mechanisms and informed decision-making are at the core of decreasing reliance on chemicals (Barzman et al., 2015). A significant negative relationship between biological control efficiency and pesticide use was found in our data, which offers empirical evidence to support the notion of ecological tradeoffs, where indiscriminate use of broad-spectrum insecticides compromises biological control services that can sustain long-term pest suppression (Yarahmadi & Rajabpour, 2024). The principal component analysis added a layer of understanding that the advantages of IPM extend beyond—and beyond—a single dimension of biological pest management to one of biological aggregates formed by three relatively independent dimensions: biological pest management, crop productivity and environmental sustainability, and economic returns with less pesticide use. This multidimensional character indicates that IPM is not just a series of alternative pest management strategies; rather, it is a system approach that can address more than one function of the agroecosystem, which is in sync with the new paradigm of ecological intensification in agriculture (Bommarco et al., 2013).

Practical implications from the results for farmers, extension workers, and policymakers aiming for moving to more sustainable pest management approaches are given. The 46.8% chemical pesticide savings realized with IPM, combined with the 19.8% higher crop yield and 21.5% greater net economic return, usually defies the assumption that a reduced reliance on chemical pesticides means a cost to the economy. Conversely, the data have also demonstrated that IPM is economically superior to conventional management, and this should help persuade farmers who may be risk-averse and might think IPM is economically inferior. The high predictability of pest monitoring frequency indicates that farmer training and provision of measurement tools (e.g., pheromone traps and/or scouting protocol) will likely produce a high benefit-to-cost ratio in terms of the effectiveness of pest suppression. Likewise, significant contribution for successfully managing pest problems by the use of resistant crop varieties, highlights the need for plant breeding that emphasizes on host plant resistance as one of the

very important pillar strategies of IPM (Dhawan & Peshin, 2009). Policymakers could use some of these insights to create incentive schemes that would lower the cost of using biological control measures, monitoring tools, and resistant cultivars, and thus speed up the shift from an overabundant reliance on chemicals. Additionally, the 28.3% increase in environmental sustainability in IPM plots indicated that implementing agricultural strategies that promote biodiversity, soil health, and environmental sustainability would also be beneficial for the provision of ecosystem services and the overall sustainability of agricultural production.

However, a few restrictions to the present study should be mentioned. First, the investigations took place in 20 agricultural research farms that, although placed in diverse agroecological zones, may not fully reflect the commercial farming system's heterogeneity, especially in developing agroecological areas where resource limitation, farmer mobility, and ease to reach the markets may impact IPM adoption and success. Training staff and having guaranteed inputs on a research farm may have influenced the level of IPM performances that were obtained, and results could overestimate the benefits that can be obtained under actual farm conditions. Second, the observation periods of two consecutive cropping seasons were adequate to measure seasonal variability but may not have been long enough to evaluate the long-term ecological and economic time scale of IPM systems. For instance, increasing populations of natural enemies and enhancing soil health could take a couple of years to become stable, and the benefits of IPM may thus be underestimated in a short-term study. Third, the use of imputation for missing values and exclusion of plots with incomplete data may have resulted in some degree of bias, especially if the missing data were not randomly distributed across treatment groups. Fourth, the study dealt with specific IPM tactics, and the effectiveness of other potentially useful tactics like push-pull systems, habitat manipulation, and application of semiochemicals was not examined. Last, the economic analysis presented was thorough and included production costs and gross revenues but did not consider potential long-term economic benefits to human health and environmental remediation from reduced pesticide use, which would also further strengthen the economic argument for IPM.

Based on the findings and limitations of this research, some directions for future research are proposed. More long-term (5-10 years) studies are needed to follow the ecological and economic trends of IPM systems over many years in order to observe the long-term impacts of the establishment of the biological control, building up soil health, and pest population changes. These studies should be extended to other farming systems, such as smallholder farming in low-income countries, to determine the applicability of the results and to discover barriers to IPM that may be system-specific. Future research should also focus on integrating new technologies like remote sensing, autonomous monitoring tools, and machine learning algorithms for pest prediction within IPM systems, which can improve the precision and timely decision-making in pest management (KO et al., 2025). Our regression model indicated a high predictive value of pest monitoring frequency in IPM effectiveness, implying that the development of improved and low-cost monitoring equipment that would be more accessible to growers may be very beneficial to enhancing the effectiveness of IPM and should be explored and evaluated. The benefits of IPM are found in ecological, agronomic, and economic dimensions, evidenced by a multidimensional structure identified by PCA, which suggests that

future studies should rely upon multiple outcome measures instead of a single indicator of potential benefits. There is also a need for research that is explicit in exposing the trade-offs and synergies among these dimensions, especially if resources are scarce, requiring farmers to trade off one dimension for another. Finally, the role of institutional and policy determinants in promoting or discouraging the adoption of IPM has not received sufficient attention, and future studies need to examine how the technical effectiveness of IPM relates with extension services, credit availability, market incentives, and regulatory factors to make IPM more or less attractive to farmers (Samiee et al., 2009).

Conclusion

The aim of this study was to understand the whole effectiveness of integrated pest management in controlling the use of chemical pesticides, maintaining agricultural productivity, and environmental health. Based on these results, it is clear that IPM has a positive effect on more than one aspect of agricultural performance, with an average decrease of 46.8 percent in chemicals and a corresponding increase of 19.8 percent in agricultural output and an increase in net economic return of 21.5 percent. The empirical confirmation of biological control efficiency and pest monitoring frequency as the best predictors for successful pest suppression according to biological principles of IPM suggests the effectiveness of using integrated control approaches, whereas the multi-dimensional structure identified from PCA indicated that the benefits of using integrated control approaches were not only biological control effectiveness but also on crop productivity and economic viability, which are relatively independent yet can be achieved simultaneously with IPM. Results add to the evidence for the viability of agriculture to produce sustainably without sacrificing productivity and contradict the notion that chemicals are essential for high yields.

References

- Barzman, M., Bàrberi, P., Birch, A., et al. (2015). Eight principles of integrated pest management: M. Barzman et al. *Agronomy for Sustainable Development*.
- Bommarco, R., Kleijn, D., & Potts, S. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution*.
- Dhawan, A., & Peshin, R. (2009). Integrated pest management: Concept, opportunities and challenges. *Integrated Pest Management: Innovation-Development Process*.
- Ediagbonya, T., Areo, I., Mupenzi, C., Mind'je, R., et al. (2025). Reduced pesticide dependency through crop management. *Discover Applied Sciences*.
- Ekström, G., & Ekbom, B. (2011). Pest control in agro-ecosystems: An ecological approach. *Critical Reviews in Plant Sciences*.
- Fahad, A. A. (2023). Modern techniques in integrated pest management to achieve sustainable agricultural development. *International Journal of Family Studies, Food Science and Nutrition Health*.
- Hawes, C., Iannetta, P., & Squire, G. (2021). Agroecological practices for whole-system sustainability. *CABI Reviews*.
- Kaur, T., & Kaur, M. (2020). *Integrated pest management: A paradigm for modern age*. intechopen.com.

KO, M. A., Alam, A., & Hotak, Y. (2025). Smart sensor technologies shaping the future of precision agriculture: Recent advances and future outlooks. *Journal of Sensors*.

Pretty, J., & Bharucha, Z. P. (2015). Integrated pest management for sustainable intensification of agriculture in asia and africa. *Insects*.

Samiee, A., Rezvanfar, A., et al. (2009). Factors influencing the adoption of integrated pest management (IPM) by wheat growers in varamin county, iran. *African Journal of Agricultural Research*.

Shah, F., & Razaq, M. (2021). From agriculture to sustainable agriculture: Prospects for improving pest management in industrial revolution 4.0. *Handbook of Smart Materials, Technologies, and Devices*.

Yarahmadi, F., & Rajabpour, A. (2024). Insecticides and natural enemies: Applications in integrated pest management programs-challenges, criteria, and evaluation for recommendations. *Pest Control-Impact, Challenges and Prospects*.