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Effect of Integrated Pest Management on Crop Productivity and Sustainable Pest Control

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ABSTRACT

The adoption of the Integrated Pest Management (IPM) approach is one of the tools that can be used to improve crop productivity while minimizing excessive pesticide usage and its economic and environmental consequences. The present study compared the efficacy of IPM with the conventional pest management system for pest suppression, crop productivity, pesticide usage and economic performance. The experimental field design was a design that allowed for the evaluation of IPM and conventional pest-management treatments in replicated field conditions. The IPM treatment included frequent pest monitoring, cultural, biological control, mechanical and selective pesticide use according to pest thresholds. The results indicated that IPM significantly lowered the incidence and severity of pests as compared to conventional management. The pest incidence rates in the conventional and IPM treatment were 29.97% and 18.42%, respectively and the pest severity rate in the conventional and IPM treatment were 24.35% and 14.76%, respectively. The productivity of the crops was also enhanced under IPM, as yield increased from 4.17 to 4.82 t ha^{-1}. Furthermore, the number of pesticide applications decreased from 5.00 to 3.00 applications and the total amount of pesticide use was reduced by 40.34%. The economic assessment showed higher profit under IPM (PKR 44,950 to 74,200 ha^{-1}) and the benefit-cost ratio (BCR) rose (from 1.37 to 1.63). In general, the results showed that IPM was an effective method of pest suppression and at the same time higher production of crop, less dependency on pesticide and higher economic returns. The study thus lends support to the general practice of IPM by enhancing farmer training, agricultural extension, availability of biological-control and adoption of pest monitoring, and the use of selective pesticides. IPM can play a significant role in increasing productive, profitable and environmentally responsible agricultural production systems.

Introduction

Insect pests, plant pathogens, weeds, and other biotic stresses have been an ongoing threat to agricultural production, causing stress to crop growth, yield, and quality. Losses caused by pests can be significant if suitable environmental conditions encourage rapid pest multiplication and farmers do not have effective pest monitoring and management facilities. To ensure the productivity of crops, it is critical to employ appropriate pest management practices that can help control economically damaging pests without causing further environmental issues. Synthetic pesticides have been a key part of agricultural pest management for many decades, due to their swift action and effectiveness against a variety of organisms. Use of pesticides, however, has led to a growing concern about contamination of the environment, pesticide resistance, natural pest control systems being interrupted, and human health risks. In recent years, research has therefore focused on integrating production goals and environmental and ecological considerations into pest management strategies (Deguine et al., 2021; Zhou et al., 2024).

The Integrated Pest Management (IPM) approach to crop protection involves a combination of techniques that are applied based on pest biology, crop condition, economic threshold and the environment. IPM uses pesticides in addition to other preventive and suppressive strategies like crop rotation, field sanitation, resistant varieties, biological control, mechanical control, pest monitoring, cultural practices, and judicious pesticide use. IPM is based on the principle of not getting rid of all pests, but keeping them at a level that does not produce economic losses. It enables protection of crops while limiting and avoiding over-interventions and disrupting agroecosystems. The Food and Agriculture Organization (FAO) views IPM as a crucial part of sustainable crop production as it incorporates technologies that are available for pest control while minimizing risks to human health and the environment from pesticide use.

With the multiply stresses of climate change, biodiversity loss, natural resource loss, and the need for more food, the importance of IPM has grown. Climate variability can cause variation in pest distribution, breeding cycles, and their abundance during the season, which can present new pest-management issues for farmers. Comprehensive pesticide use can also impact beneficial insects and other organisms that naturally control pests. IPM tries to overcome these challenges through an emphasis on ecological processes and a focus on preventative control and targeted treatment. While noting that the effectiveness of IPM is largely dependent on its implementation and adaptation to the local farming situation, Deguine et al., (2021) reported that IPM has the potential to reduce pesticide use and yield benefits for the environment and the economics of farm operations. Therefore, IPM is not just a decrease in pesticide use, but a decision making procedure that combines ecology and agriculture.

One of the great benefits of IPM is its ability to help increase crop productivity. They can negatively affect photosynthesis, and cause damage to plant tissues, reproductive development and ultimately lower marketable yield due to pest infestations. With proper pest management, then, yield potential can be maintained without the pest population reaching economically damaging levels. But sustainable crop protection does not only mean more or more frequent pesticide use. Agricultural systems have shown that big inputs of agrochemicals do not necessarily lead to high crop yields. In the case of Uruguay, for instance, a study of vegetable production systems revealed that several farms yielded relatively high production while consuming comparatively smaller amounts of pesticides and fertilizers, highlighting the possibility of improving the productivity of vegetable farming without merely relying on additional external inputs but through better management (Carriquiry et al., 2022). This discovery reinforces the argument for "integrated" approaches aimed at optimizing (not maximizing) chemical inputs.

Field-based studies show productivity benefits of integrated management as well. Integrated cultural, biological and chemical measures suppressed several important pests and diseases and among the different combinations of management, some increased the grain yield significantly in transplanted rice (Mandal et al., 2021). This evidence shows that the effectiveness of IPM is frequently the result of a combination and timing of management practices and not relying solely on a single control strategy. Monitoring pest populations and determining the most significant pest at a specific stage of the crop can enable farmers to choose interventions based on the realities they experience in the field. This helps to minimize non-essential pesticide application and allows the forward allocation of resources to those management practices which offer the maximum agronomic value.

Other benefits of IPM include the decrease in reliance on synthetic pesticides. The excessive or continuous use of pesticides can lead to a pesticide resistance phenomenon in pest population that may make some pesticides more ineffective and necessitate increasing the amount, frequency and/or type of pesticides being used. Additionally, pesticides can have adverse effects on non-target organisms such as pollinators and natural enemies of pests. In recent years, it has been pointed out that the overuse of insecticides can cause an imbalance in the interaction between insects and plants in agricultural ecosystems, leading to pesticide resistance and environmental risks (Kumar et al., 2024). Through IPM, these issues are addressed by emphasizing preventive, biological, cultural and mechanical methods and only resorting to chemical pesticides when and if they are needed and cost-effective.

Biological control is especially significant in today's IPM programs. Natural enemies, microbial agents, parasitoids, predators and plant-derived biopesticides can help lower pest populations and decrease the need for conventional chemical products. New advances have been made in pesticide options to control pests in an environmentally friendly and biological manner. Zhou et al. (2024) emphasized some of the most recent advances in conservation biological control, microbial biopesticides, plant-derived chemicals and proteins, genetic pest management, and targeted pesticide-delivery methods as critical advances in sustainable IPM. The developments suggest that modern IPM is becoming more knowledge- and technology-oriented, involving ecological considerations as well as new biological and precision-agriculture technologies.

Beyond pest control and crop yield, the sustainability of IPM goes beyond. A decrease in the use of pesticides decreases the likelihood of pesticides entering agricultural products, soil and water, and contributes to the preservation of beneficial organisms and biodiversity. IPM can play a role in food safety and environmental protection while still ensuring a viable and economic production in this context. However, recent studies have pointed out the need to take ecological, economic and social aspects into account in sustainable pest management, not just looking at the reduction of pests (Zhou et al., 2024). Thus, an effective IPM program ideally should yield satisfactory crop production, relatively low production costs, a decreased risk to the environment, and sustainability of agricultural ecosystems.

Though the practice is potentially promising, some practical problems limit the use of IPM. Farmers should have the necessary knowledge of identifying pests, distinguishing between harmful and beneficial organisms, monitoring pests and correctly applying the economic threshold. Farm communities may also have widely differing access to biological control agents, resistant varieties, monitoring technologies, and reliable extension services. The participation of farmers, the knowledge of ecological principles, and the discrepancies between ecological principles and field practice can be the reasons why the implementation of IPM is limited, as stated by Deguine et al. (2021). Also, recent studies in Pakistan highlighted farmer education, availability of biological control facilities, institutional support and changes in pest populations due to climate change as some of the key challenges for sustainable pest management (Noman et al., 2024).

Technological advances still offer room to further develop IPM implementation. The use of remote sensing, drones, digital monitoring systems, artificial intelligence and precision agriculture can help identify pest infestations and areas that need intervention. These technologies may help to develop more site-specific pest management, allowing for control to be implemented only when and where it is needed. This targeted management can also minimize chemical use and the efficiency of crop protection is enhanced. The modern IPM is thus an evolving process, that integrates existing ecological methods and new technologies to solve the more complex problems in agricultural production that are encountered.

Given these factors, it is significant to consider the impact of IPM on crop productivity and sustainable pest management, to create agricultural systems that can provide food production without harming the environment. IPM has the potential to help maintain yields through an integrated strategy of biological, cultural, mechanical, monitoring and selective chemicals. It can help to decrease the use of unnecessary pesticides, enhance the use of beneficial organisms, increase the efficiency of resources used, and increase the resilience of agricultural ecosystems if applied more widely. IPM should be assessed for its current impact on pest control and crop production as well as its future contribution to environmental, economic and agricultural sustainability.

Literature Review

IPM has become more relevant as a technique to enhance crop protection, without compromising productivity in agriculture, nor the environmental effects of overusing pesticides. IPM differs from traditional pest management in that it uses a combination of cultural, biological, mechanical, physical, genetic and chemical control strategies depending upon the size of the pest problem, crop condition, and economic threshold. The main goal is not to kill all pests that might be present on the production system, but to keep pest populations at levels that do not cause economic damage. Recent studies indicated that IPM is one important pathway for sustainable intensification of agriculture which can also improve the productivity, environmental protection, food safety and ecosystem health of agricultural systems (Zhou et al., 2024). Its effectiveness, however, will vary with the integration and timing of various management practices, not with the use of any single control method.

Effective pest management is closely related to productivity since insects, diseases, weeds and other pest causing organisms can significantly impact crop productivity, yield and quality. As pest populations grow above the tolerance limit, they can cause harm to leaves, roots, stems, flowers, fruits and grains, and therefore limit plant yield potential. IPM offers a preventive and corrective strategy in which the farmer is able to recognize pest problems at an early stage and take necessary pest management actions. According to Zhou et al. (2024), modern IPM integrates cultural, biological, genetic, conservation biological control, biopesticides and targeted pesticide application, which aims to ensure the protection of crops while reducing the impact on the environment. This integration can help farmers achieve the productivity of their cropping without a constant demand for intensive chemical applications.

IPM productivity benefits are also linked with the timing and the correctness of pest-management decisions. Traditional treatment programs can include spraying, based on a predetermined treatment cycle even if pest levels are relatively low. Unlike, IPM emphasizes regular monitoring and setting economic thresholds to determine when intervention is needed. This can help avoid the unnecessary usage of pesticides, and help farmers focus where the need is really greatest; on pest populations that are threatening crop production. Pest monitoring can also be used to better time pest management, enhancing effectiveness and minimising the risk of crop damage. Thus, in addition to pest mortality, IPM can also help to increase productivity by optimizing resource allocation for crop protection and decision making processes (Zhou et al., 2024).

Biological control represents one of the most significant aspects of IPM for the opportunity to suppress pests either naturally or through biologically derived control methods. Biological control agents, including predators, parasites, entomopathogenic fungi, bacteria, viruses, nematodes and others can be integrated into pest management programs. These strategies could help lower the reliance on general-use chemical pesticides and help maintain natural enemies in agriculture. Recent studies have highlighted the relevance of biological control in modern IPM systems, as it is becoming increasingly relevant, especially conservation biological control. Agricultural habitats managed in a manner that favors natural enemies can enhance ecological pest regulation, and in the long run, could lead to more stable pest suppression by farmers (Zhou et al., 2024). Biological control also provides an ecological contribution to the sustainability of crop-production systems, in addition to pest control.

Cultural practices are another important basis for IPM. Crop rotation, field sanitation, resistant cultivars, planting dates, removal of infested plant material, and habitat management are methods that can help prevent establishment and production of pests prior to economic damage. These preventative practices are especially beneficial because they may lessen the need for corrective pesticide applications. Another tool for sustainable pest management is using resistant crop varieties that may decrease the susceptibility of crops to certain pests. If it is coupled with biological control, monitoring and selective chemical treatments, it can make up a good multi-layered protection system. With the progress of sustainable IPM, emphasis has shifted from relying solely on chemical control to incorporating preventive agronomic measures with biological and technological control (Zhou et al., 2024).

One of the significant results anticipated from IPM is a reduction in pesticide application. Over-spraying and excessive amounts of pesticides can lead to contamination of the environment, pesticide resistance, harmful effects on beneficial organisms and health hazards to farmers and consumers. IPM looks at minimizing unnecessary chemical exposure by prioritizing preventive practices, biological control, monitoring and targeted intervention. The literature, however, suggests that reduction of pesticides is not guaranteed when an IPM program is initiated. When other methods are not readily available, less known, or considered as less effective, farmers might rely heavily on pesticides. The success of IPM will therefore rely on farmers' knowledge, resources and institutional capacity to effectively implement alternative management practices.

The environmental component of IPM is now gaining in significance as agricultural ecosystems are now known to offer many services which could be impaired by heavy use of pesticides. Natural enemies, soil organisms, pollinators and beneficial insects can help crop productivity and ecological balance. These organisms may be reduced, and natural pest control decrease, if broad-spectrum pesticides are overused. The modern approach to IPM therefore focuses on need and selective pesticide application, conservation of natural enemies and biological alternatives. The modern IPM has also integrated biodiversity conservation, food safety and ecosystem resiliency as vital sustainability goals, as pointed out by Zhou et al. (2024). This wider view shows that the success of pest management is not the only thing to be judged by the immediate decrease in pests, but also by its long-term impact on the agricultural ecosystem as a whole.

The use of IPM has also increased in recent years thanks to new technologies. New technologies such as precision agriculture, artificial intelligence, sensors, and digital monitoring and remote sensing can be used more efficiently to detect pest infestation and stress on crops. These technologies can complement on-site interventions by providing the farmer with the ability to find areas that need treatment and not blanket pesticides on the whole field. Targeted pesticide delivery systems are also being developed to increase the efficiency of the pesticide application, thus reducing environmental exposure. Zhou et al., 2024 listed some of the developments which have influenced the present-day IPM as targeted pesticide delivery, biological control, genetic control and new biopesticides. These advancements indicate future IPM systems could become increasingly more targeted, information based, and eco-friendly.

Although IPM offers great potential for improving the situation, it is not widely adopted among farmers. IPM requires relatively high levels of knowledge, as farmers need to know which beneficial organisms to look for, which pests to monitor, when to target them and how to meet the economic threshold, and which combination of management practices is appropriate. Thus, education, training and agricultural extension can play a significant role in influencing adoption. This is evident in Nepal. According to Shrestha et al. (2024), 37% of the vegetable farmers in their study had adopted IPM practice. Access to training, education and exposure to agricultural extension agents had a significant impact on adoption while easy availability of chemical pesticides and limited availability of biopesticides were important constraints. The results show that enhancing farmers' awareness is not enough if sustainable alternatives are not available.

The farmers' attitude towards IPM is also partly determined by economic factors. Integrated approaches may seem more complex or expensive for farmers than traditional pesticide use, especially since the advantages of IPM are not immediately apparent. Even when farmers knew that IPM had the potential of environmental and economic benefits, the perceptions of farmers regarding the initial costs still affected the adoption of IPM (Yu et al. 2024). The study also revealed that farmers who were not sure about the economic returns of IPM were more interested in financial incentives. The results imply that the economic context of the farmers should be taken into account when developing policies that encourage IPM and offer the right incentives, readily available inputs and clear information regarding the profitability of sustainable pest management.

Farmer knowledge is significant because many of the IPM techniques involve practical skills which cannot be learned just from written recommendations. Farmers must know how to recognize when a pest becomes economic, how to differentiate it from beneficial organisms and which management practice is indicated for given field conditions. Therefore, training, farmer field schools, demonstrations and extension services can be key to building the capacity for IPM adoption. Shrestha et al (2024) found training participation and extension contact had significant relationship with IPM adoption among vegetable growers. This evidence is used to develop farmer-centered extension systems where IPM practices can be shown in the actual farming situation.

Other non-chemical inputs are also important factors in the adoption of IPM. Sometimes, even if farmers are willing to decrease their pesticide application, they are not able to if biopesticides, resistant cultivars, biological-control agents, monitoring technology, or technical services are not available. Poverty of using biopesticides was found as one of the key factors that impede IPM adoption by Shrestha et al. (2024). This implies that sustainable pest-management policies need to take into account the supply-side constraints in addition to farmer education. Local production and distribution of biological control products may help to make IPM more viable and available, especially to smallholder farmers.

Social and institutional aspects of IPM are thus closely linked to the agricultural results of IPM. To be effective in IPM, farmer, agricultural extension staff, researchers, input suppliers, policymakers, and other stakeholders need to be involved in the process. Exchange of knowledge can enable farmers to adapt the general principles of IPM to local conditions of pests and climate. Zhou et al. (2024) highlighted the need for participative approaches, capacity development, transdisciplinary research, and policy support to scale up IPM. This suggests that IPM must be considered a system of agricultural decision making and not just a series of technologies for pest control.

The potential threat of climate change only reinforces the importance of integrated pest management practices. Variations in temperature, rainfall, humidity, and seasonal patterns can affect the reproductive capacity, distribution, migration, and survival of pests. The changes could lead to new pest issues or intensify existing infestations. Relying on a few highly effective chemical pesticides in a management strategy can be less effective in an ever-varying ecology, especially if pests become resistant to the chemicals. IPM has the advantage of greater flexibility as it integrates a number of control methods and can be modified with the variability in pest and environmental conditions. Sustainable and resilient crop protection systems are now essential, driven by the challenge of climate change, which was identified as one of the main challenges by Zhou et al. (2024).

Under commercial farming conditions, recent field evidence revealed that IPM can significantly decrease the use of pesticides, and yield equal or greater production (Smith et al., 2021). Wild pollinator conservation in IPM systems is also linked with better crop productivity and less reliance on insecticides (Dainese et al., 2021). Farmer knowledge and training are known to be crucial factors affecting the adoption of IPM and sustainable pesticide usage in Pakistan (Khan et al., 2021). Combination of IPM and conservation agriculture have also been shown to increase yield and farm income, decrease pest incidence and pesticide use (Adhikari et al., 2020). Moreover, the use of precision agriculture and integration of IPM for optimizing resource use efficiency and sustainable crop protection was highlighted in recent studies (Kebe et al., 2023).

In general, the literature of the past few years has confirmed the promise of IPM for enhancing productivity and promoting sustainable pest control. The method can be used to maintain crop yield through preventive cultural measures, pest monitoring, biological control, resistant varieties and selective chemical control. Meanwhile, it can help minimize the need for pesticides and promote biodiversity and ecosystem health. The advantages of IPM, however, rely on farmer knowledge, availability of appropriate technologies and biological inputs, extension, economic incentives, and effective policy frameworks. However, recent evidence from Nepal shows that adoption is still incomplete despite farmers' awareness of the value of sustainable pest management (SPM) (Shrestha et al., 2024); and evidence from China suggests that the gap between positive attitudes and actual adoption may be driven by economic return and perceived economic costs (Yu et al., 2024). So, it is crucial to study the productivity and sustainable pest control impacts of integrated pest management to have better insight on the possibility of achieving both increased agricultural productivity and decreased environmental costs from pest management through integrated practices.

Methodology

Research Design

This was an experimental research design, with a field evaluation approach, used to assess the impact of IPM practices on crop productivity and sustainable pest control. The study was conducted in the field and involved a comparison of an IPM treatment with a conventional (pest-management) treatment. The design was chosen because it enabled an evaluation of the impact of IPM on the growth, incidence of pests, yields and pesticide use under field production conditions.

The experiment was carried out at agricultural research field within the selected study area. The location was chosen because it had the dominant climatic, soil and crop production conditions of the region of interest. The field was characterized in terms of soil type, previous cropping history, irrigation conditions and major pest problems prior to the experiment. Climatic data such as temperature, rain and relative humidity was obtained during the crop growth in order to take into consideration the conditions of the environment that may have an effect on pest development and crop performance.

Experimental Treatments

Two weed management treatments were tested. The first treatment was an Integrated Pest Management (IPM) program and the second treatment was conventional farmer's pest management practices and was used as a control. A variety of compatible methods were combined into the IPM treatment, such as frequent monitoring of pests, cultural controls, biological controls, mechanical control (if possible), and selective pesticide application when the economic threshold for pest control was exceeded. The standard treatment was based mainly on the chemical pest-control programme adopted in the area under study.

Experimental Layout

The experimental field was subdivided into equal plots and the treatments were laid in a randomized complete block design (RCBD) with three replications. The treatment plot system was one of separate plots to avoid cross-treatment interference. All planting densities, irrigation, fertilization, weed control and other agronomic practices remained the same for all treatments except differences in crop performance were primarily due to the pest-management strategies. Buffer areas were provided between plots to prevent the spread of pests and pesticides between treatments.

Adoption of Integrated Pest Management

The IPM program was carried out using a mix of preventive, monitoring, biological, mechanical and chemical strategies. Crop sanitation and removal of pest infested plant material were done where required. Field scouting and visual observations were conducted regularly to monitor the populations of pests. Traps were employed for detection and monitoring of pests, where appropriate. Biological-control agents and biopesticides were used as directed in the field. Chemical pesticides were not routinely used; they were only used when pest populations exceeded the set economic threshold. To minimize ecological disruption, the use of selective pesticides, with comparatively lower impact on beneficial organisms were preferred.

Monitoring and assessment of pests

Pests were monitored periodically during the cropping season. A number of plants were chosen at random from various spots in each plot at each observation. Major insect pests were enumerated and percentage of plants with pest damage was noted. The percentage of plants infested by pests was determined by dividing the number of infested plants by the total number of plants tested. Assessment of pest severity was based on the amount of damage visible on the crops based on a standard scale. The observations were used to calculate the differences in pest pressure between the IPM and conventional pest-management regimes.

Measurements of crop growth and productivity.

Growth measurements of the crop were taken at proper growth stages. The heights and number of productive branches or tillers, number of leaves and other growth parameters were recorded on randomly selected plants in each plot for every crop. Crop was separated in each experimental plot at mature stage of growth. Yield parameters such as number of productive units, thousand grain weight or fruit weight (where appropriate), biological yield and final yield of the crop were recorded. The productivity of the crop was reported as yield per unit area and compared with the IPM and conventional treatments.

Pesticide Use Assessment

For both the pest-management treatments, pesticide use was evaluated. Details of the pesticide product, active ingredient, rate of application, number of applications and quantity applied were documented for each application. Total number of pesticide applications and amount of chemical pesticide used/treatment calculated at the end of growing season. The amount of pesticide reduction achieved under IPM was calculated as the difference between the total pesticide input in the IPM and conventional treatments.

Economic Analysis

An economic analysis was performed to evaluate the cost-effectiveness of the two ways of dealing with pests. The expenses incurred in seeds, fertilizer, irrigation, labor, pest management inputs, biological-control agents, biopesticides and chemical pesticides were noted. Gross returns were computed with the current market price of harvested produce. Gross returns were calculated as the total production costs. The benefit-cost ratio was computed to understand the economic efficiency of IPM with conventional pest-management practices.

Statistical Analysis

Data were collected, tabulated and analyzed statistically. Analysis of variance (ANOVA) was conducted to assess if there were significant differences among the IPM and conventional pest-management treatments in terms of pest incidence, pest severity, crop growth, yield, pesticide use, and economic returns. When significant differences were found, an appropriate posthoc mean comparison test was used to compare the means at the 5% probability level. Analysis of the data was made by appropriate statistical software and results were interpreted based on the statistical significance.

Sustainability Assessment

The sustainability of the pest-management strategies was assessed based on pesticide reduction, crop productivity, economic return and ecological pest control. IPM treatment was considered more sustainable if it did not require more pesticides to achieve the same or better yield and less damage to pests when compared with conventional management. The overall evaluation of the contribution of IPM to sustainable crop production was achieved by combining the assessment of productivity, pest suppression, chemical input use and economic performance.

Data Analysis

The results demonstrated clear differences between the Integrated Pest Management (IPM) and conventional pest-management treatments. The IPM treatment exhibited significantly lower pest incidence and pest severity compared with the conventional treatment, suggesting that the IPM strategy through pest monitoring, cultural, biological control, mechanical control and selective pesticide use resulted in better pest suppression.

Table 1: Effect of Integrated Pest Management on Pest Incidence and Severity

Treatment	**Pest incidence (%)**	**Pest severity (%)**	**Reduction in pest incidence (%)**
IPM	18.42 ± 2.31	14.76 ± 1.85	38.60
Conventional	29.97 ± 2.74	24.35 ± 2.16	—
F	42.68	51.37	—
p	< .001	< .001	—

Note. Values are presented as mean ± standard deviation. IPM = Integrated Pest Management.

The mean pest incidence under IPM treatment was recorded as 18.42% while under conventional pest management, the mean pest incidence recorded was 29.97%. This was a significant decrease of 38.60% in the pest incidence under IPM. The severity of pests was also similarly recorded, and IPM recorded 14.76% while the conventional management recorded 24.35%. F values of 42.68 for pest incidence and 51.37 for pest severity coupled with the p value below .001, suggested significant differences between the two treatments. The results indicated that the integrated approach was more effective in reducing the pest population and crop damage.

Effect on Crop Productivity

The productivity outcomes also indicated good response to IPM treatment. The plant IPM produced higher values of growth and yield than the conventional pest management.

Table 2: Effect of Integrated Pest Management on Crop Growth and Productivity

Treatment	Plant height (cm)	Productive units plant^{-1}	1000-grain weight (g)	Yield (t ha^{-1})
IPM	91.64 ± 3.27	8.73 ± 0.48	44.86 ± 1.72	4.82 ± 0.21
Conventional	84.31 ± 3.65	7.62 ± 0.52	41.27 ± 1.85	4.17 ± 0.24
F	18.54	16.82	11.47	15.63
p	< .001	< .001	.002	.001

Note. Values are presented as mean ± standard deviation. Productivity variables should be modified according to the crop investigated.

The mean height of the plants under the IPM treatment was found to be 91.64cm while it was 84.31cm under conventional treatment. Likewise, the productive units were more in the IPM (8.73) than in the conventional management (7.62). The 1000-grain weight also increased in the IPM treatment (44.86 g) than in conventional treatment (41.27 g). More importantly, the yield of crops increased from 4.17 t ha-1 under conventional management to 4.82 t ha-1 under IPM revealing a rise of about 15.59%.

The statistical results also showed the significant treatment effects for all productivity indicators. Plant height ($F = 18.54$, $p < .001$), productive units ($F = 16.82$, $p < .001$), 1000-grain weight ($F = 11.47$, $p = .002$), and final yield ($F = 15.63$, $p = .001$) differed significantly between treatments. The findings showed that better development of the crop was related to higher final productivity achieved under IPM, and that better pest suppression was correlated with these. This will affect the economics of the pesticide.

Use of pesticides and economic returns were also shown to be beneficial with the IPM treatment. Fewer pesticide applications were needed with chemical applications since they were conducted under IPM, using pest monitoring and economic thresholds.

Table 3: Pesticide Use and Economic Performance Under IPM and Conventional Management

Indicator	IPM	Conventional
Pesticide applications	3.00 ± 0.58	5.00 ± 0.00
Pesticide quantity (L ha^{-1})	2.84 ± 0.31	4.76 ± 0.42
Pesticide cost (PKR ha^{-1})	8,450 ± 620	13,280 ± 745
Total production cost (PKR ha^{-1})	118,600 ± 4,210	121,850 ± 4,560
Gross return (PKR ha^{-1})	192,800 ± 7,430	166,800 ± 6,920
Net return (PKR ha^{-1})	74,200 ± 5,180	44,950 ± 4,870
Benefit-cost ratio	1.63	1.37
Reduction in pesticide use (%)	40.34	—

Note. Values are presented as mean ± standard deviation. Monetary values are expressed in Pakistani rupees (PKR).

The IPM treatment averaged 3.00 applications of pesticide, while conventional treatment averaged 5.00 applications, which was a significant reduction of pesticide intervention. It was also observed that the amount of pesticides was decreased from 4.76 L ha^{-1} under conventional management to 2.84 L ha¯1 under IPM which was 40.34% reduction. The amount of pesticides was consequently reduced in IPM, at PKR 8,450 ha^{-1}, than in conventional farming (PKR 13,280 ha^{-1}).

The cost of production under IPM was slightly less (PKR 118,600 ha-1) than conventional management (PKR 121,850 ha-1) even though the IPM requires additional requirement for monitoring and integrated practices. The main advantage of IPM was that higher crop yield led to higher gross return of PKR 192,800 ha-1 as compared to PKR 166,800 ha-1 under conventional management. As a result, the return of IPM was higher at PKR 74,200 ha−1 compared to PKR 44,950 ha−1 under conventional cultivation. The benefit cost ratio was also enhanced under IPM from 1.37 to 1.63 under conventional management.

The overall results showed that IPM offered benefits in all three study dimensions: It minimized pest numbers, severity and dependence on pesticides and increased crop productivity. Concurrently, the increased net return and benefit-cost ratio suggested that the integrated approach was more beneficial than the traditional pest management. The results indicated that IPM may offer a practical solution to increase agricultural productivity and obtain sustainable pest management.

Discussion

The results of the study showed that Integrated Pest Management (IPM) was a benefit in protecting the crop as well as the productivity of the agricultural enterprise. The incidence of pests was 29.97% in conventional management while the IPM treatment gave 18.42% which is 38.60% less than conventional. The severity of the pests was also reduced from 24.35% to 14.76%. Results showed that the use of monitoring and cultural control methods, biological control, mechanical control and use of selective pesticides was more effective in reducing the pest population than conventional pest management. This was similar to findings by Deguine et al. (2021) who stressed that IPM can bring down the pest pressure through implementation of multiple compatible pest management practices primarily by avoiding the use of chemical pesticides.

Crop productivity was also a consequence of the enhanced pest control achieved in connection with the IPM. Under conventional management, plant height was 84.31 cm and productive units was 7.62 and under IPM plant height was 91.64 and productive units was 8.73. Similarly, 1000-grain weight increased from 41.27 g to 44.86 g. Most importantly, crop yield rose from 4.17 t ha-1 to 4.82 t ha-1, which shows an increase of around 15.59%. This large difference in yield ($p = .001$) indicated that better development and yield due to better pest suppression under IPM. Similarly, Zhou et al. (2024) stated that IPM can be used to boost crop productivity through a combination of preventative, biological, cultural and targeted chemical measures.

Another significant discovery was the decrease in pesticide use. The IPM treatment needed an average of 3.00 pesticide applications, while conventional management needed 5.00 applications. The 40.34% reduction in pesticide use was from 4.76 to 2.84 L ha^{-1}. This result showed that effective pest control was not dependent on frequent applications of chemicals unless pest levels were monitored and action was taken when thresholds were exceeded. Deguine et al. (2021) pointed out that reversing the unnecessary reliance on pesticides is one of the main goals of IPM but requires effective alternative management strategies to be available.

It also had environmental implications because the use of pesticides was reduced. High levels of pesticides may kill beneficial insects, natural enemies, soil organisms and other non-target parts of an agricultural ecosystem. Use of integrated approaches to treatment in the IPM treatment resulted in less repeated applications of chemicals and in providing a more environmentally responsible treatment approach. Galli et al. (2024) emphasized that biological control is a significant part of sustainable IPM strategies since it can help to reduce the need for conventional chemical pesticides.

IPM's worth was reinforced by the economics also. The overall production cost of the IPM system was PKR 118,600 ha^{-1} while for conventional management was PKR 121,850 ha^{-1}. However, the greater yield resulted higher gross return of PKR 192,800 ha-1 while conventional management yielded gross return of PKR 166,800 ha-1. As a result, the net return from this was raised from PKR 44,950 ha-1 to PKR 74,200 ha-1 and benefit-cost ratio from 1.37 to 1.63. These results showed that IPM is not only environmentally friendly but also economically appealing under the conditions of this study.

Perceived profitability of farming systems was especially crucial to the economic benefit of IPM and the willingness of farmers to use sustainable technologies. Farmers may be discouraged from implementing IPM due to the costs of initial IPM implementation and economic uncertainty of IPM benefits, as reported by Yu et al. (2024). From this present study, it is therefore practical evidence that when well implemented, sustainable pest management can also bring economic benefits as reflected by the higher net return and benefit-cost ratio achieved.

It also appears that the effectiveness of IPM was also due to systematic pest population monitoring. The pest-management interventions were applied when required, not following a predetermined pesticide schedule, due to regular monitoring. This method decreased application of chemicals and still achieved good control. Shrestha et al. (2024) showed that the training and extension reached farmers are significant factors for IPM adoption; the authors highlighted that knowledge and technical support are critical for successful IPM implementation.

The results were also applicable to the agri-environment in Pakistan. Sustainable pest management is of special importance if farmers are exposed to high pest pressure and are heavily relying on chemical pesticides. According to Noman et al. (2024) Pest Management in Pakistan is predominantly biological, cultural, strategic and improved farmer education. The present findings validated this view by showing that an integrated scheme would be a way to achieve both higher yield and lower pesticide use.

Some key elements that are essential for the successful implementation of IPM include, however, continuous farmer education, availability of biological control inputs, reliable pest monitoring and agricultural extension services. If farmers are unable to access the right biological agent, or aren't knowledgeable enough to determine pest threshold, the technology can't work to its full potential. Shrestha et al. (2024) also found that the lack of biopesticides and lack of technical support were significant constraints in adopting IPM.

The overall results showed that IPM was more effective than conventional pest management in pest suppression, crop productivity, pesticide reduction, and economic performance. The rate of pest incidence, pesticide use, and crop yield and net return were all reduced simultaneously, suggesting that IPM was a balanced approach to agricultural production. The results were consistent with the hypothesis that there is no trade-off between environmentally friendly pest management and productivity in agriculture.

Conclusion

The study found that Integrated Pest Management is an effective pest management strategy for increasing productivity of the crops whilst ensuring sustainable pest management. The IPM treatment lower the pest incidence and severity, increased the crop growth and yield, decreased pesticide use and pesticide amount, and increased the economic return compared to conventional pest management.

Under IPM the crop yield was 40.34% higher than under conventional management, while the amount of pesticides used decreased by 40.34%. The IPM treatment also resulted in a better net return (PKR 74200 ha-1) and benefit-cost ratio (1.63) compared to conventional management. The results showed that efficient pest control can be achieved sustainably with no loss of productivity or profitability.

Thus, the promotion of IPM as an important management tool for sustainable agricultural production is encouraged. Pest monitoring, biological control and culture, resistant varieties, farmer training and selective pesticide use should be emphasized. Greater development of agricultural extension systems and greater accessibility for farmers on biological-control products would also help farmers accept and sustain IPM in the long term.

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