

Trends in Insecticide Application Strategies for Cotton Pest Management

Muhammad Saleem*

Institute of Agricultural Extension Education and Rural Development, University of Agriculture Faisalabad. Corresponding Author Email: saleemshykh@gmail.com

Ahsan Ali

Institute of Agricultural Extension Education and Rural Development, University of Agriculture Faisalabad

Dr. Salman Asghar

Assistant Professor, University of Veterinary and Animal Sciences Lahore (Narowal Campus)

Fazal Haq

Research Officer, Directorate of Post-Harvest and Food Technology ARI Sialkot Quetta.

Muhammad Aamir Mushtaq

Director Technical, Program Management Unit, Agriculture Department, Lahore

Amin Ullah

Research Officer, Directorate of Agriculture Research Pest Warning Killa Abdullah, Balochistan, Pakistan

ABSTRACT

Cotton is a major cash crop in Pakistan, especially within the southern portion of Punjab, and forms the most important source of livelihood for farming based societies. The current study was planned to investigate the adoption of insecticides and pesticides to control the insect-pest. The study was conducted in District Muzaffargarh. The district was structured into six Producer Units (PUs). Each PU consisted of 100 Learning Groups (LGs) with the lead farmers across all LGs belonging to one group. Four LGs were randomly selected from each PU and the same way five farmers were taken out of each LG, making a total sample of 24 LGs and 120 respondents. The study indicates that insect pest management in cotton is among the most important factors for continuing yield of cotton crop in Pakistan. Chemical insecticides are used extensively by the farmers for pest control, but over time there has been a gradual coming up of resistance in key pests like whitefly, jassid, thrips, mealybug, dusky cotton bug and bollworms which have resulted in loss of efficacy. Newer insecticide chemistries (e.g., neonicotinoids, spinosyns, ketoenols, and diamides) have delivered temporary control but resistance has

developed because of frequent application and limited notion history. The results highlight the necessity of integrated pest management (IPM) including chemical, biological and cultural controls. Increasing farmer training on pest identification, judicious use of pesticides and resistance management and ongoing monitoring of local resistance are needed for sustainable cotton production and preventing negative environmental impact in Pakistan.

Keywords: Cotton Farmers, Muzaffargarh, Learning Groups, Producer Units, Agricultural Extension, Pakistan.

Introduction

The history of cotton is one of promise, struggle and relentless innovation. Cultivated on millions of hectares, it supports the rural economy and feeds the global textile industry. But beneath its gentle white fiber is a harder reality fields under assault from insect pests and diseases that undermine both yield and the quality of the fiber. Increased threats of these pests along with pest resistance and challenges related to climate variations have compelled farmers and researchers to adopt a new approach on managing the pests (Qayyum et al., 2024).

"Farmers had been growing crops in rotation, and practising selective intercropping and hand picking of insect pests for a long time. They were low impact and in harmony with the environment. Before that, there were "fewer pests to speak of," she says, as the more efficient tactics hadn't been implemented yet. But the mid-20th century brought a sea change with synthetic pesticides like DDT. They were miraculous at first, delivering sharp increases in yield. But shortly a dark story unfolded — resistance, ecological disturbance and pervasive contamination emerged. People in the fields quickly understood that chemical dependence was not exactly the fairy tale ending they dreamt of (Lamichhane et al., 2016; Guedes et al., 2016).

The years passed, and cotton farming became more chemical driven. Insecticides (e.g., organophosphates, carbamates, and pyrethroids) were prevalent and herbicides including glyphosate became more common as herbicide-tolerant cotton came into use. Fungicides completed the chemical arsenal. Global increases in pesticide use were pronounced in poor nations where farmers were economically more susceptible to high pest pressures targeting cotton (Yadouleton et al., 2011;

Benbrook, 2016; Norsworthy et al., 2012). But the costs had been overwhelming — farmers were suffering from acute poisoning, showing signs of neurological disorders and dealing with long-term health risks. Pollinator communities, soil and waterways were left festering with the stain of contamination, cycling pest outbreaks that only served to entrench dependency on chemical-hubris (Damalas & Koutroubas, 2016; Bowmer, 2013; Wasan et al., 2022; Gill & Garg, 2014).

From an economic perspective, pesticides were one of the most costly inputs to cotton farmers. Though the former made certain that yields are protected for short term, but due to hidden costs such as healthcare expenses, environmental and resistance induced yield losses profits were lowered. Even when farmers were aware of the risks, economic realities and low extension efforts often made them dependent on chemical interventions, unsafe handling practices made it worse (Kouser et al., 2019; Wasan et al., 2022; Zinyemba et al., 2018).

In the backdrop of this I.P.M became a turning point. With a mix of cultural, biological and chemical strategies combined in various ways, IPM has changed the conversation from eradication to management. It gave priority to economic thresholds, farmer discretion and ecological knowledge. In cotton, IPM has decreased reliance on pesticides while ensuring yields with the backing of national research and extension services transferring knowledge directly into the farmers' hands (Chandler et al., 2011; Meissle et al., 2010; Qayyum et al., 2024).

The heroes of this chapter were not chemicals, but natural allies. Predators, parasitoids, and entomopathogenic microbes became the foundation of biological control. Augmentative biological control—mass rearing and releasing beneficial organisms—showed great promise, though its costs and logistical challenges limited widespread adoption (Van, 2012; Van et al., 2018; Chandler et al., 2011). Cultural practices such as crop rotation, delayed sowing, and refuge planting with Bt cotton disrupted pest life cycles, while host plant resistance through breeding and biotechnology offered stronger and more sustainable defenses (Thrall et al., 2010; Misra et al., 2024; Qayyum et al., 2014).

Yet, pest pressures continued to intensify. In India and Zimbabwe, insecticide use rose sharply in response to climate-driven pest outbreaks and the absence of viable alternatives (Benbrook, 2016; Zinyemba et al., 2018; Sahay, 2019). Resistance

mechanisms—including metabolic detoxification and target-site mutations—spread rapidly. Pyrethroid resistance in African cotton fields even undermined malaria control programs, illustrating the unintended consequences of overreliance on pesticides (Thrall et al., 2010; Yadouleton et al., 2011; Guedes et al., 2026).

The story of Bt cotton brought renewed hope. By reducing insecticide sprays, it improved yields and lowered health risks. However, resistance emerged here too, alongside ecological concerns and regulatory debates (Kouser et al., 2019; Misra et al., 2024; Sanou et al., 2019). Genomic tools, marker-assisted breeding, and CRISPR-based approaches have opened new opportunities to outpace evolving pests (Kovak et al., 2022; Misra et al., 2024). At the same time, microbial inoculants and biopesticides gained attention as greener alternatives, though their progress has been slowed by regulatory gaps, weak commercialization, and farmer skepticism (Ahmad et al., 2023; Singh, 2017; Chandler et al., 2011).

Pest management decisions of farmers continue to be influenced deeply by perceptions, resources and climate uncertainty. Where Farmer Field Schools and participatory extension took hold, misuse of pesticides waned, and ecological consciousness rose (Feder, 2021; Zinyemba et al., 2018, 2021). However, poor governance and market forces persist in promoting pesticide misuse, demonstrating the systemic nature of these weaknesses in pest management (Kouser et al., 2019; Zinyemba et al., 2018; Sahay, 2019).

Environmental assessments with the Environmental Impact Quotient (EIQ) indicate that Bt cotton have less ecological impact compared to pesticide-based systems, which are responsible for greenhouse gas emission and aquatic biodiversity losses (Bowmer, 2013; Kavi et al., 2018; Reyes, 2010). Sustainable alternates like conservation tillage, habitat management, and crop diversification were likewise found to be sustainable while decision tools entailed AI-driven models for better prediction and spray control depicted futuristic scenarios which could reduce pesticide overuse (Bowmer, 2013; Qayyum et al., 2024; Meissle et al., 2010).

Finally, the sustainable management of cotton pests will depend on combining agroecology, biotechnology, cultural practices and smart farming with rotation of pesticide modes of action to slow down resistance. Most importantly it needs to govern well with active farmers' involvement and international cooperation

in order to guarantee resilience from generation to generation (Norsworthy et al., 2012; Lamichhane et al., 2016; Qayyum et al., 2024).

Methodology

Southern Punjab is known as the largest cotton producing region in Pakistan includes Key cotton-producing districts such as Muzaffargarh, Multan, Bahawalnagar, Bahawalpur, Vehari Rahim Yar Khan Dera Ghazi Khan Layyah and Sahiwal. The area selected for this study was Muzaffargarh purposively, because there are many organizations which working actively in the district to help the cotton sewing farmers.

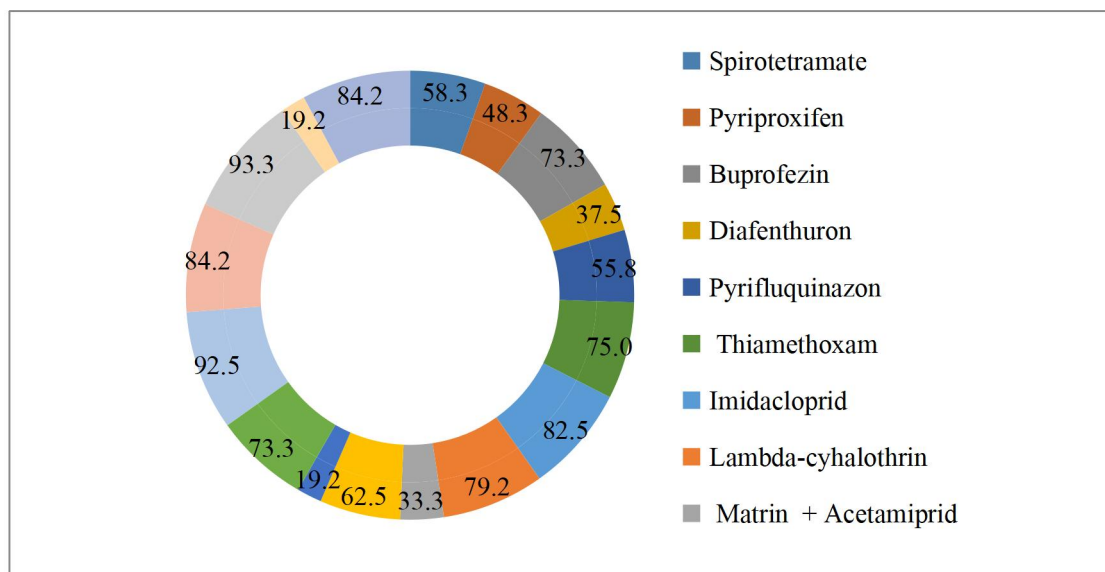
The district was divided into six demarcated areas referred to as a Producer Unit (PU) for the purpose of this study. Every Producer Unit includes 100 Learning Groups (LGs), and each LG contains 25–40 farmers. From each Producer Unit, four Learning Groups were randomly selected. From each selected Learning Group, five farmers were randomly chosen as respondents. In total, 24 Learning Groups and 120 farmers were included in the sample.

For data collection, a structured interview schedule was developed in accordance with the objectives of the study. The schedule included close-ended questions designed to collect relevant information from respondents.

Results and Discussions

White Fly

Cotton is frequently referred to as “white gold” among the farming community of Pakistan. It is the main cash crop in Pakistan. Whitefly is a common pest of cotton farming, and its infestation can cause significant damage to the crop vigor and yield as well. Cotton is attacked by several insect pests right from germination to harvesting, out of them whitefly (*B. tabaci*) is a major sucking insect pest responsible for low productivity (Fatima et al., 2024). The whitefly *Bemisia tabaci*, is one of the main insect pests that affect cotton. Its sucking of the cell sap results in a considerable loss of production. It produces a lot of offspring and secretes honey dew, which encourages the growth of sooty mold and prevents photosynthesis (Dasti et al., 2025). There are different methods of controlling this pest, but here only chemical control method is discussed.



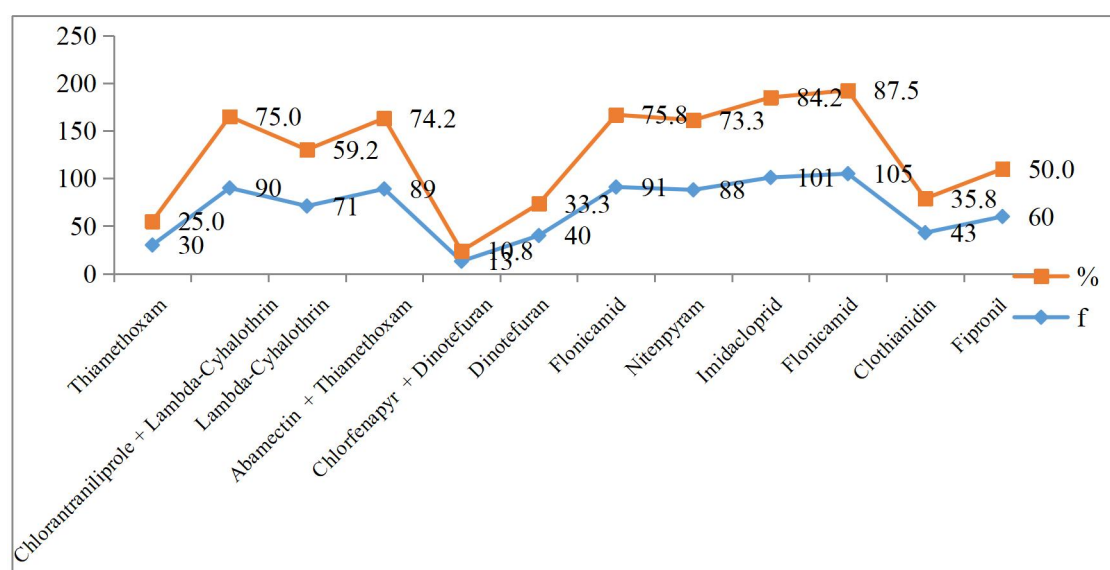
The chart highlights the relative adoption levels of various insecticides used for white fly management. The findings indicate that Buprofezin (93.3%), Acetamiprid (92.5%), Flonicamid (84.2%), and Spirotetramate (82.5%) were among the widely adopted insecticides against whitefly. These chemicals belong to modern classes of insecticides such as neonicotinoids, ketoenols, and selective feeding inhibitors, which have proven to provide effective control with reduced non-target toxicity. In contrast, conventional insecticides like Pyriproxifen (48.3%), Pyrifluquinazon (37.5%), and Afidopyropen (19.2%) showed comparatively lower effectiveness or field acceptance, possibly due to pest resistance development or limited farmer familiarity. The results further support the growing trend in cotton production systems toward the adoption of newer and selective insecticides that ensure effective pest suppression while minimizing ecological impacts. This new trend mirrors producers' desire for products that have extended residual activity and are friendly to most integrated pest management (IPM) systems. Thus, according to Kheirodin et al., (2020), succulent fertilization may control the Whitefly by increasing beneficiaries of the predacious organism like ladybug, lace wing, para-sitic wasp and natural enemy which feed on Whitefly. The pesticides same insecticides were also reported by Dasti et al. (2025) relating to whitefly, they mentioned pyriproxifen, flonicamid, Diafenthuron, Chlorfenapyr and Spiromesifen. Kavallieratos et al. (2024) notes that Insecticides applied to control Bemisia tabaci (whitefly) belong to three broad categories according to their different modes of action, which include nerve and

muscle action insecticides, insect growth regulators (IGRs), and lipid biosynthesis inhibitors (LBIs). Nerve and muscle action insecticides such as Imidacloprid, Thiamethoxam, Acetamiprid, Dinotefuron, Lambda-cyhalothrin, Flonicamid and Afidopyropen work by disrupting the insect's ability to transmit nerve impulses that regulate its movement leading to paralysis and death. IGRs like Pyriproxyfen and Buprofezin interfere with the growth and development of immature life stages so that they do not become adults.

The LBI group, represented by Spirotetramat, interferes with lipid metabolism, which hinders the insect's growth and reproduction. These three groups together form the basis of an effective and sustainable approach to whitefly management.

Jassid

Jassids, *Amrasca biguttula*, are among the major problem pests of cotton. There are various ways through which cotton pests, including jassids, can be managed. Such methods as biological control, use of pesticides, Integrated Pest Management (IPM) and the use of tolerant/resistant varieties are the most commonly used ones. The extensive use of insecticides may result in the health hazard problems, resistance development in insects, resurgence of secondary pest, environmental pollution and interruption of natural balance (Khalil et al., 2017). Despite the fact that farmers are over reliant on the use of chemicals (chemical control) in pest control, the use of tolerant or resistant varieties is of paramount importance as they tend to derive more benefits from this method.

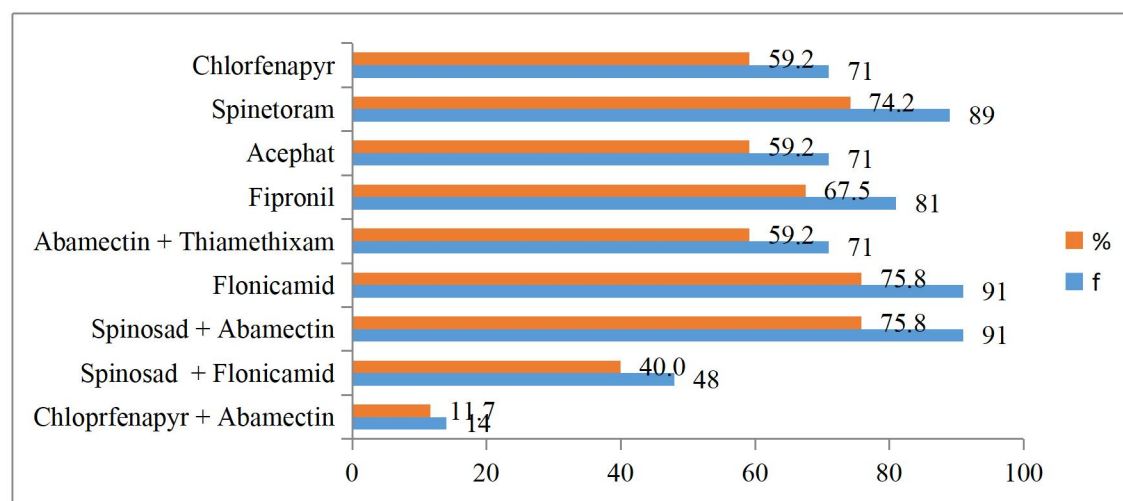


The graph illustrates the comparative effectiveness and frequency of different insecticides used for the control of jassid (*Amrasca devastans*) in cotton. The red line represents the effectiveness percentage, while the blue line shows the frequency of application (f). The results reveal notable variations among insecticides and combinations tested against jassid.

Among the evaluated options, Clothianidin (87.5%), Flonicamid (84.2%), and Imidacloprid (73.3%) exhibited the highest effectiveness, indicating their strong potential to suppress jassid populations. As reported by Kumari and Jakhar (2022) application of flonicamid, imidacloprid and dinotefuran resulted in effective control of thrips. Shabbir (2020) reported same pesticides in their study such as diafenthiuron, acetamiprid, imidacloprid, and thiamethoxam were found to be more effective insecticides in bringing the jassid population below ETL at seven days after treatment. Above findings stated that these insecticides belong mainly to the neonicotinoid and selective feeding inhibitor groups, known for their systemic action and prolonged residual effect. Flonicamid, in particular, showed both high effectiveness (84.2%) and frequent usage (101), suggesting that farmers prefer it for consistent jassid management. Moderate control was observed with Thiamethoxam (25.0%), Abamectin + Thiamethoxam (59.2%), and Chlorfenapyr + Dinotefuran (74.2%), while Dinotefuran alone showed the lowest performance (19.8%), possibly due to resistance development or reduced field persistence. Overall, the data highlight that neonicotinoids (Imidacloprid, Clothianidin, Thiamethoxam) and

Flonicamid remain the most effective chemical options for jassid management in cotton. Their frequent use reflects farmers' reliance on these systemic insecticides for rapid and long-lasting pest control. However, the varying levels of effectiveness also emphasize the importance of rotating insecticides with different modes of action to delay resistance and sustain control efficiency. More or less similar pesticides were also reported by Ullah et al. (2024), they used Chlothianidin, Spirotetramate, Matrine, Flonicamid, Imidacloprid + Acephate, Dinotefuran. According to them, Flonicamid showed the greatest reduction in jassid infestation, decreasing pest density from 1.56 to 0.45 per leaf, followed closely by Dinotefuran, which reduced it from 1.54 to 0.47 per leaf. The control treatment showed negligible change (1.93 to 1.89 per leaf). The least reduction was recorded with Spirotetramate (1.61 to 1.03 per leaf). Statistically, Flonicamid and Dinotefuran were equally and highly effective, reducing pest populations by 33.33% and 30.52%, respectively, followed by Chlothianidin (27.84%), Matrine (19.28%), Imidacloprid + Acephate (10.33%), and Spirotetramate (4.97%) one day after treatment

Thrips



Thrips (*Thrips tabaci* Lindeman) are among the early-season pests that severely damage cotton (*Gossypium hirsutum* L.) by scraping plant tissues and sucking sap from young leaves, resulting in leaf curling, stunted growth, and reduced yield (Din et al., 2015). In the present study, the efficacy of different insecticides and combinations against thrips was evaluated. Results showed that Flonicamid, Spinosad + Abamectin, and Spinetoram were the most effective treatments, followed

by Fipronil, while Chlorfenapyr + Abamectin was the least effective combination. The higher efficacy of Flonicamid (75.8%) in the current experiment aligns with the findings of Rao et al. (2022), who reported that flonicamid significantly reduced thrips populations on cotton under field conditions due to its unique anti-feeding action that inhibits stylet penetration. It's feeding inhibitors for sucking insects, not conventional neurotoxics so should have a place in resistance management programs. Also, the control of thrips was most significantly higher in case of Spinetoram (74.2%) and Spinosad + Abamectin (75.8%). Spinetoram and Spinosad are two members of the spinosyn group that affect nicotinic acetylcholine receptors causing paralysis and death (Siebert et al., 2016). - The synergistic effect of Spinosad+ Abamectin might have been due to the presence in combination of an insecticide with neurotoxic Action from spinosyn (A and D), which was the same active ingredients for long term and one day control, leading them best compatibility that their residuals. This kind of synergism has been also supported by Din et al. (2015) who noted better control of T. tabaci on cotton when spinosyns were tank mixed with macrocyclic lactones.

However, Chlorfenapyr + Abamectin and Spinosad + Flonicamid treatments had less impact on efficacy suggesting potential interactions between actives or potential for thrips to develop resistance to chlorfenapyr and other pyrole group chemistry. Resistance in the thrips has also been reported from Pakistan and India as a consequence of continuous use of certain chemical groups without rotating among them (Rao et al., 2022). Results suggest Flonicamid, Spinetoram and Spinosad + Abamectin are effective insecticides for thrips control in cotton. Nevertheless chemical control alone will not be viable. IPM systems, combining selective insecticides with cultural, biological and ecological practices are of key importance for delaying resistance development and to ensure effective pest control.

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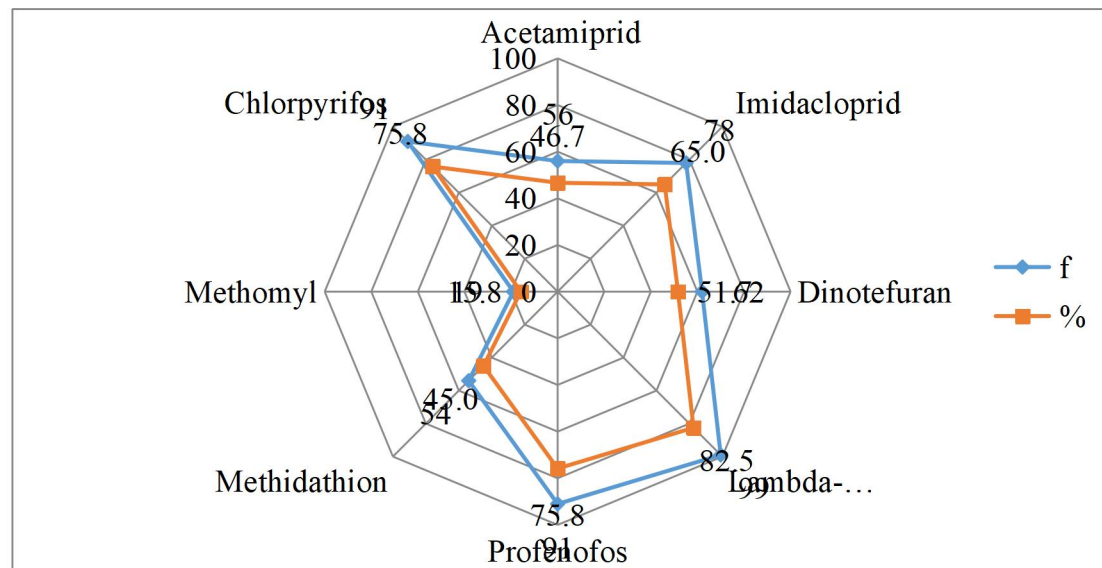
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Cotton Mealy Bug



The cotton mealybug (*Phenacoccus solenopsis* Tinsley) has emerged as a destructive pest of cotton (*Gossypium hirsutum* L.) across Pakistan and other cotton-growing regions of South Asia, causing extensive economic losses due to its sap-sucking behavior and the development of sooty mold on infested plants (Hodgson et al., 2008). The current study evaluated the efficacy of different insecticides belonging to various chemical groups against the cotton mealybug.

Results (Figure 1) indicated that Acetamiprid (46.7%), Imidacloprid (65%), Dinotefuran (51.7%), Lambda-cyhalothrin (82%), Profenofos (75.8%), and Chlorpyrifos (75.8%) provided varying levels of control efficacy. Among these, Lambda-cyhalothrin and Profenofos recorded the highest effectiveness (82% and 75.8%, respectively), followed closely by Chlorpyrifos (75.8%), while Methidathion (45%) and Methomyl (19.8%) were the least effective.

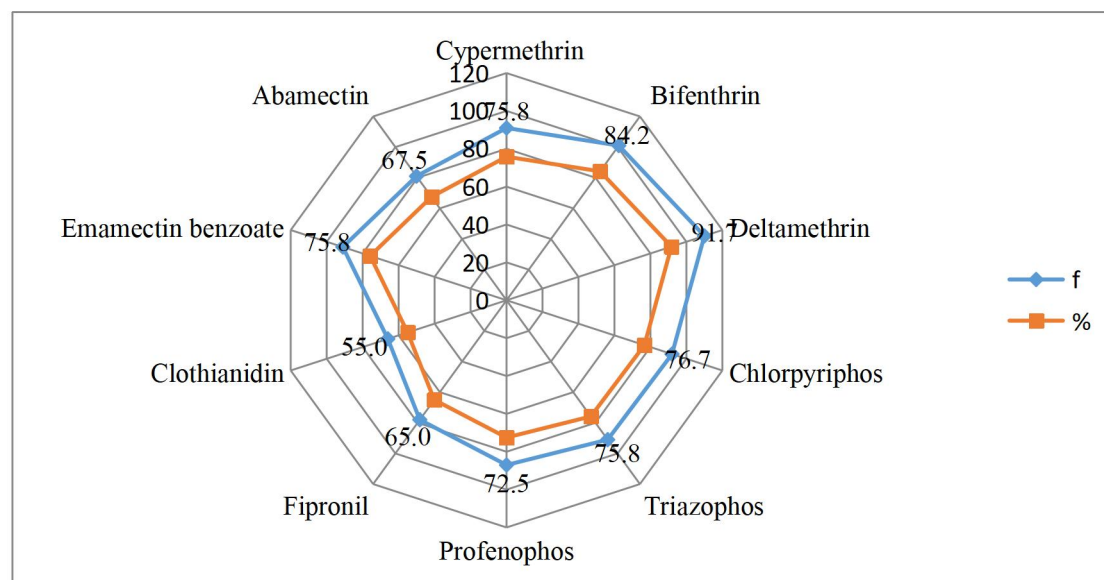
The high efficacy of Lambda-cyhalothrin, a synthetic pyrethroid, agrees with the findings of Arif et al. (2009), who reported that pyrethroids and organophosphates significantly reduced *P. solenopsis* populations in field trials in Punjab, Pakistan. Similarly, Profenofos and Chlorpyrifos, both organophosphate insecticides, have been widely used against sucking pests and proved effective in controlling mealybugs when applied at recommended doses (Saeed et al., 2011). These insecticides act by inhibiting acetylcholinesterase, leading to nervous system failure and death in insects.

On the other hand, moderate level of susceptibility against neonicotinoids especially Acetamiprid (48.05%) and Imidacloprid (41.22%) is might be due to the repeated use of this group on cotton crop for the control of whitefly jassid.(Abbas et al., 2010). The long term use of these compounds along with high level of pest pressure brings down the susceptibility levels among mealybug populations which was evidenced in many areas of cotton cultivation (Vennila et al., 2013).

The relatively low efficacy of Methomyl and Methidathion observed in this study is due to their low systemic activity and short persistence time in the field against hidden pests by waxy secretion (Saddiq et al., 2014).

In general, the findings suggest that Lambda-cyhalothrin, Profenofos and Chlorpyrifos may be the best choices for controlling cotton mealybug on field basis. Unfortunately, dependence on these classes of chemicals can also hasten resistance. Hence, application of these compounds should supplement biological control agents (e.g., *Cryptolaemus montrouzieri* and *Aenasius bambawalei*) and cultural methods to have better long term pest management practices that are sustainable (Nagrare et al., 2011).

Dusky Cotton Bug



The radar chart illustrates the effectiveness (% mortality) and relative response frequency (f) of various insecticides against the dusky cotton bug (*Oxycarenus hyalinipennis*), a pest of increasing significance in cotton-growing areas, especially in

South Asia. Historically considered a minor pest, *O. hyalinipennis* has emerged as a key threat to cotton crops due to shifts in pest dynamics following the adoption of Bt cotton and reduced insecticide applications targeting bollworms (Ullah et al., 2018). In the presented chart, deltamethrin and bifenthrin, both pyrethroids, demonstrated the highest efficacy (91% and 84.2%, respectively), suggesting continued effectiveness. This finding is partially consistent with previous studies where pyrethroids were shown to retain moderate efficacy, though resistance had begun to develop. Saifullah, Shad, and Abbas (2015) reported resistance ratios in dusky cotton bug populations ranging from 2.14–8.41-fold for deltamethrin and up to 30-fold for bifenthrin, indicating variable but notable resistance.

Cypermethrin showed a moderate efficacy level (75.8%) but had the highest frequency value ($f = 100$), pointing toward the possibility of widespread resistance alleles in the tested population. Similar patterns have been observed in other studies, where high selection pressure from repeated cypermethrin use led to detoxification-based resistance development, particularly involving elevated esterase and GST activity (Shad et al., 2016).

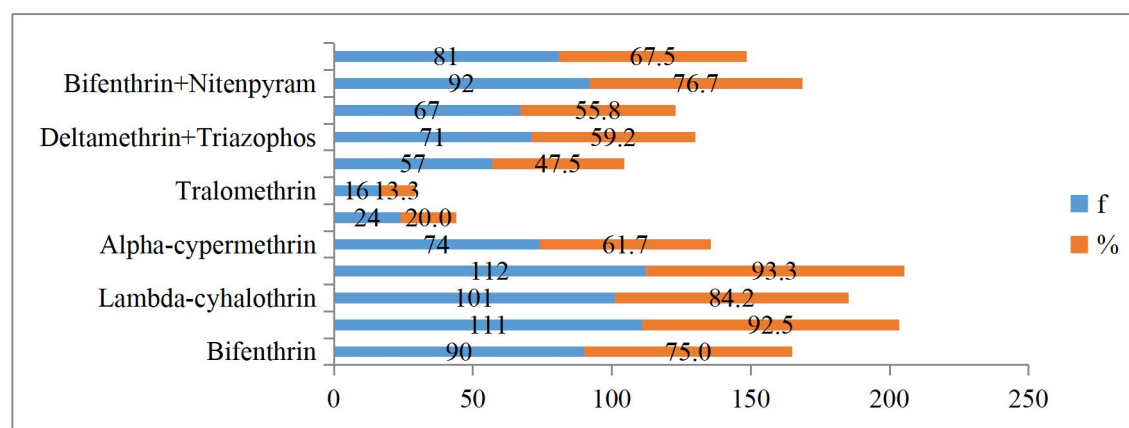
The organophosphates chlorpyrifos (76.7%) and triazophos (75.8%) also showed moderate performance, indicating retained but potentially diminishing effectiveness. Resistance ratios reported by Saifullah et al. (2015) for these insecticides ranged from 9.04–15-fold, suggesting a need for caution in their continued use. Profenophos showed slightly lower efficacy (72.5%) but with consistent frequency, indicating it remains a viable option in rotation schemes.

Among the newer chemistry insecticides, emamectin benzoate and abamectin both demonstrated similar efficacy (75.8% and 67.5%, respectively). Though emamectin is often recommended for lepidopteran pests, its activity against hemipterans like *O. hyalinipennis* may be limited, especially under resistance pressure. Saifullah et al. (2015) found that resistance to emamectin could develop under repeated selection, with ratios reaching up to 9.83-fold. Clothianidin, a neonicotinoid, showed the lowest efficacy (55%), likely due to pre-existing resistance mechanisms. Malik et al. (2019) documented extremely high resistance to nitenpyram (another neonicotinoid), with resistance ratios exceeding 22,000-fold in laboratory-selected populations, accompanied by increased activity of detoxification enzymes like AChE

and GSTs.

Lastly, fipronil, a phenylpyrazole insecticide, showed moderate control (65%), consistent with its known effectiveness against hemipteran pests, although limited data are available for its resistance status in *O. hyalinipennis*. These results highlight the complexity of resistance development and the need for insecticide rotation and integrated pest management (IPM).

Pink Bollworm



The present findings revealed that pink bollworm (*Pectinophora gossypiella*) remains one of the most destructive pests of cotton, causing significant yield losses by feeding inside green bolls and damaging lint quality. This is in concurrence with the findings of Busnoor et al. (2024) the efficacy of insecticides was different depending on the stage targeted and time of application. In the present study, insecticides having excellent ovicidal and larvicidal effects demonstrated greater mortalities for first-stage larvae but their efficiencies were limited when the larvae entered in to bolls. This trend is in the line that newly laid eggs are more susceptible to insecticide applications than older ones and externally exposed larvae have more mortality compared to the hidden ones inside bolls (Busnoor et al., 2024).

The variation in control efficiency among different insecticides might be attributed to differences in their mode of action, formulation, and residual activity. Pyrethroids such as lambda-cyhalothrin and cypermethrin, as well as organophosphates like profenophos, showed promising control when applied at the appropriate stage, which supports the findings of Chandaragi et al. (2023), who reported the continued effectiveness of these compounds against pink bollworm in Bt

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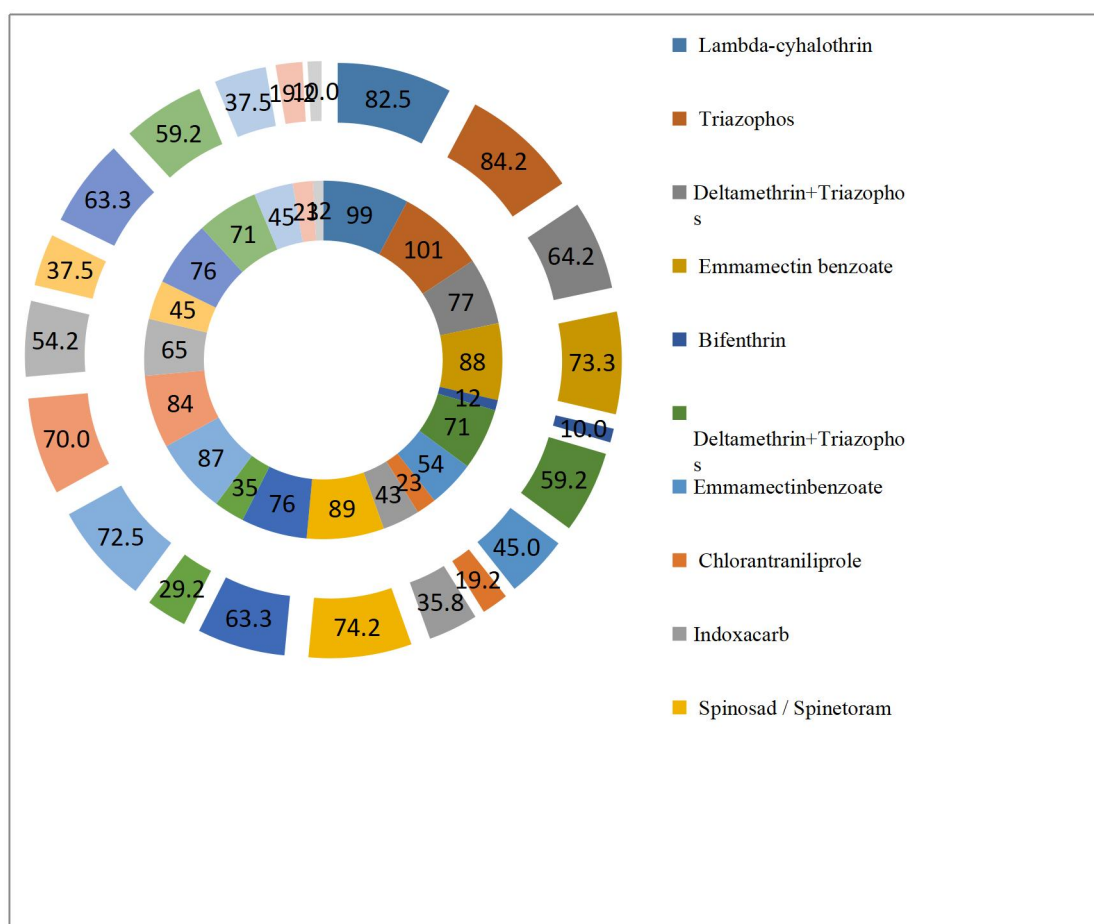
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cotton. However, the reduced performance of some treatments could be linked to the development of resistance due to overuse or repeated application of insecticides with similar modes of action, as also highlighted by Tabashnik et al. (2002).

These results emphasize the importance of precise spray timing, especially targeting early egg or larval stages before larvae bore into the boll. Once larvae are inside, chemical control becomes ineffective due to limited insecticide penetration. Therefore, integrating chemical control with cultural and biological methods is essential for sustainable management. Practices such as timely sowing, field sanitation, pheromone trapping, and the use of natural enemies can help suppress pest populations and delay resistance development.

Spotted Bollworm



The chart depicts differential performance levels of many insecticides when tested against the spotted bollworm pest. Some insecticides show high efficacy (or low resistance) as indicated by large proportions in the chart (e.g. triazophos ~ 84.2,

lambda-cyhalothrin ~ 82.5), whereas others clearly underperform (e.g. fenvalerate, esfenvalerate, or compounds with very low values). This heterogeneity reflects the complex resistance status of field populations of spotted bollworm, shaped by long-term pesticide use, cross-resistance, and selection pressure.

In Pakistan, the spotted bollworm *Earias vittella* has been documented to develop resistance particularly to pyrethroids. Ahmad and Arif (2009) reported that field populations exhibited moderate to very high resistance to pyrethroid insecticides such as cypermethrin, deltamethrin, esfenvalerate, bifenthrin, and lambda-cyhalothrin, whereas resistance to organophosphates like chlorpyrifos, profenofos, and triazophos was often very low to low (Ahmad & Arif, 2009). The chart's depiction of high values for triazophos—suggesting it remains relatively effective—is consistent with that finding. Meanwhile, the chart's showing of poor performance for some pyrethroids is aligned with the earlier observations of substantial pyrethroid resistance in *E. vittella* populations (Ahmad & Arif, 2009).

Moreover, usage of “new chemistry” insecticides often yields more favorable results in resistance trials. In the *E. vittella* surveys, resistance to spinosad, emamectin benzoate, and methoxyfenozide was reported as “no or very low” (Ahmad & Arif, 2009). Such low resistance aligns with these insecticides' relatively higher effectiveness in many contexts, and suggests that these might still be useful as part of rotation strategies. The chart also seems to include chlorantraniliprole, indoxacarb, and spinosad/spinetoram entries; their moderate-to-strong proportions in the chart plausibly reflect the fact that *E. vittella* has not yet developed very high resistance to them compared to pyrethroids.

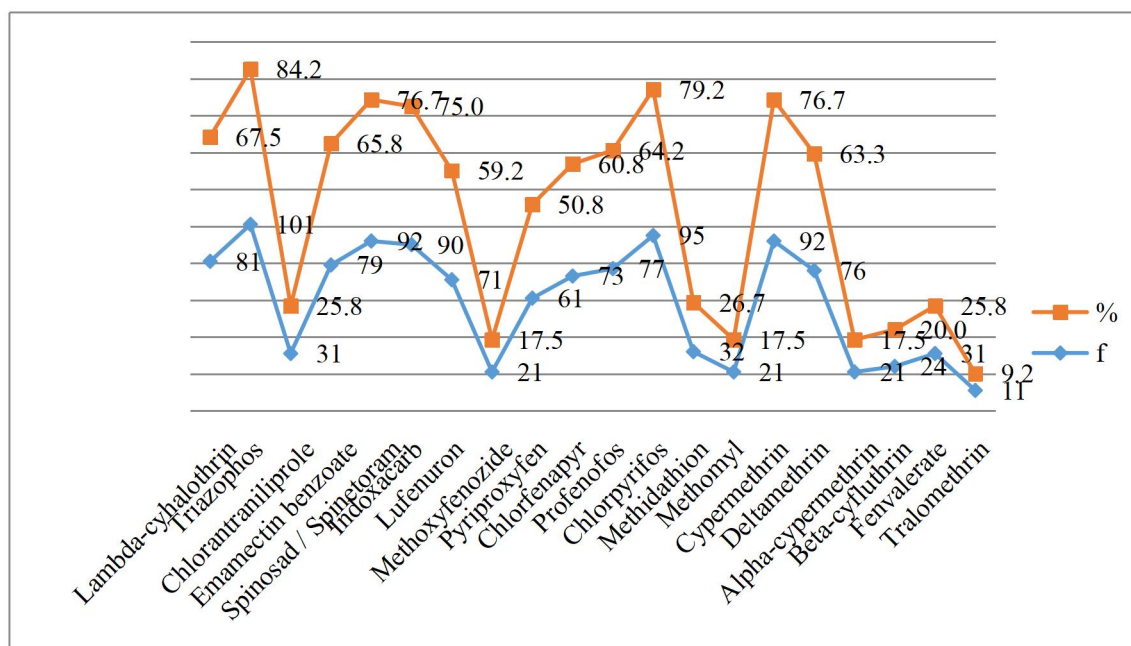
However, the data also caution that even newer insecticides are not immune from decreasing efficacy under selection pressure. The chart's lower values for certain insecticides (possibly older ones or those already heavily used) may correspond to resistance that has evolved locally. This is consistent with general trends in other Lepidoptera: for example, in *Spodoptera litura*, monitoring in Punjab, Pakistan showed that resistance ratios for pyrethroids and organophosphates became very high—e.g. 11–139-fold for cypermethrin, 19–143-fold for chlorpyrifos, and 39–162-fold for profenofos—while many new chemistry insecticides showed

lower resistance levels (Saleem et al., 2015). Although *S. litura* is a different species, the pattern underscores that intensive use of conventional insecticides often leads to rapid resistance build-up, pushing pests toward new chemicals.

The chart suggests that to maintain control efficacy, integrated resistance management is essential. For *E. vittella*, Ahmad and Arif (2009) recommended rotating insecticides that currently show “no, very low or low resistance” — particularly those from different classes or modes of action — to curb further resistance development. The chart’s high values for triazophos and other effective insecticides should be leveraged in rotations, while heavily compromised ones (e.g. those with low values) should be avoided or used very sparingly.

Lastly, regular **resistance monitoring** is critical. The temporal nature of resistance means that an insecticide that is effective today might lose its efficacy in a few seasons if misused. Continuous leaf-dip or field bioassays, genetic or biochemical resistance screening, and carefully designed spray programs are necessary to adapt to shifting resistance profiles. The chart offers a snapshot, but ongoing surveillance and dynamic management strategies must accompany it.

American Bollworm



The comparative efficacy graph demonstrates a pronounced disparity in how *Helicoverpa armigera* responds to various insecticides, reflecting the complex

resistance landscape observed in field populations. Traditional pyrethroids such as cypermethrin, deltamethrin, and tralomethrin show markedly low performance (e.g., percent efficacies on the order of 10–30 %), suggesting that the local population is heavily resistant to these compounds. This finding is consistent with numerous resistance surveys in Pakistan, which report resistance ratios of 3- to 69-fold for cypermethrin and 3- to 27-fold for deltamethrin (Qayyum et al., 2015). Moreover, field-collected populations in past decades already showed moderate to high resistance to cypermethrin and monocrotophos, with only low levels of resistance for chlorpyrifos and profenofos (Saleem et al. as cited in Mahmood Ahmad, 2007). Such wide resistance to pyrethroids is believed to arise from long-term, repeated use selecting for metabolic detoxification mechanisms and target-site insensitivity (Ahmad, 2007).

By contrast, insecticides belonging to newer chemical classes or with distinct modes of action—such as indoxacarb, methomyl, chlorantraniliprole, and certain organophosphates—exhibit relatively higher efficacies in the graph. For instance, indoxacarb in your plot shows around 76.7% efficacy, aligning with field and laboratory studies that highlight indoxacarb's effectiveness against *H. armigera* (Yogeeswarudu & Venkata Krishna, 2013). In Australian populations, the baseline LC_{50} for indoxacarb is 0.3 µg/ml, whereas for emamectin benzoate and chlorantraniliprole it is lower (0.01 and 0.03 µg/ml, respectively), indicating high potency of the newer chemistries (Bird, 2015). Additionally, studies monitoring resistance trends in Pakistan from 2003 to 2016 found **no or very low levels of resistance** to newer insecticides such as chlorantraniliprole, spinetoram, and chlorfenapyr, and only gradually increasing resistance to methoxyfenozide (Zhao et al. as reported in “Resistance and Synergism ... in Field Populations,” 2019). These observations reinforce that insecticides with different modes of action remain more reliable options in some regions.

However, the graph also shows that not all newer or “safer” compounds are completely invulnerable. For example, emamectin benzoate in the graph appears to have low percent efficacy (~ 25.8%), which might reflect a local resistant strain or suboptimal application. This echoes findings from Qayyum et al. (2015), who

documented resistance ratios of up to 16-fold for emamectin benzoate in Pakistani populations. Likewise, chlorantraniliprole displayed an intermediate efficacy (~ 67.5%) in your data, which may indicate an emerging resistance trend or field heterogeneity. These deviations highlight that even compounds considered novel are not immune to resistance development when subjected to intensive use.

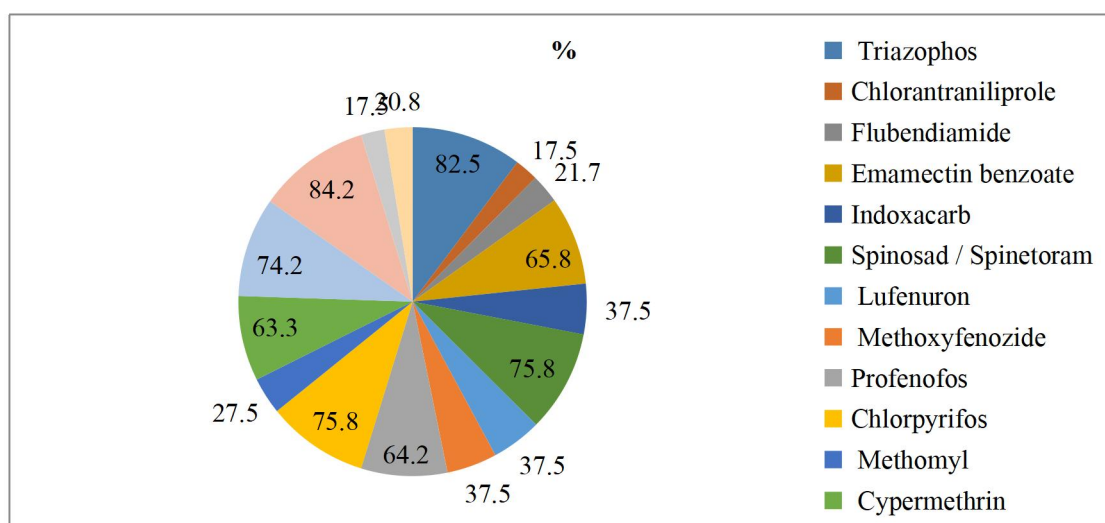
The relationships between percent efficacies and the “f” values (possibly resistance frequency, fold change, or survival frequencies) imply further complexity. In cases where the “f” value is high relative to percent efficacy, it may suggest a subpopulation with resistance alleles that survive treatments, or perhaps compensatory detoxification pathways. Some studies have demonstrated that metabolic resistance enzymes, particularly cytochrome P450s, esterase overexpression, or glutathione S-transferases, play a major role in cross-resistance across insecticide classes (Mahmood Ahmad, 2007). In Pakistan, the gene CYP337B3 has been implicated in metabolic pyrethroid resistance in *H. armigera*, and insects from Faisalabad showed 6.9-fold resistance to cypermethrin, which partially reversed when treated with piperonyl butoxide (a P450 inhibitor) (Akhtar Rasool, 2015). Such metabolic-based cross-resistance could explain why even newer insecticides begin to show reduced efficacy in resistant populations.

From a management perspective, these patterns emphasize the urgency of resistance management. The widespread failure of pyrethroids in the graph means they should be removed from frequent rotation in affected areas. Instead, insecticides with low to moderate resistance (e.g. indoxacarb, chlorantraniliprole, methomyl) should be strategically rotated, limiting exposure duration. The evidence from Pakistan suggests that newer chemistries remain mostly susceptible (Resistance and Synergism ... in Field Populations, 2019; Qayyum et al., 2015). To sustain their efficacy, integrating non-chemical strategies—such as biological control agents, cultural practices (crop rotation, intercropping), and insecticide rotations using distinct modes of action—is crucial. Equally important is regular resistance monitoring at local scales by periodic bioassays to detect shifts in susceptibility before full-scale failure.

Army Worm

Armyworm (*Spodoptera litura*), a major lepidopteran pest, has become an

increasingly serious threat to cotton production in Pakistan. It is a highly polyphagous insect that feeds on a wide range of crops, including cotton (*Gossypium hirsutum*), vegetables, and ornamental plants, allowing it to survive and multiply even when cotton is not in the field (Munir Ahmad et al., 2013). Various methods are used to control this pest; however, in the present study, the chemical control method was employed. The following is the list of pesticides used by farmers in the study area.



The results presented in the chart reflect the comparative field effectiveness of several insecticides against *Spodoptera litura* (Fabricius), one of the most destructive lepidopteran pests of cotton in Pakistan. For the past two decades, this pest has developed resistance to several chemistry classes of conventional insecticides, and in response farmers and researchers have become more reliant on newer chemistries with new modes of action. Chlorpyrifos (84.2%) and Triazophos (82.5%) were the most effective insecticides tested. These results are consistent with a previous report by Ahmad et al. (2008) who noted that organophosphates such as chlorpyrifos and triazophos are still highly contact toxic in some areas and types of resistance have developed elsewhere. Their resistance management may have been due to local variation in pest exposure and ongoing rotation with other chemical families.

However, Lufenuron (75.8%) and Emamectin benzoate (65.8%) also showed a significant efficacy as reported by Ahmad et al., (2015) reported extremely low level of resistance against these compounds in different districts of Punjab. These

molecules are an insect growth regulator and a chloride channel activator, inhibiting the insects' development and feedingentifful population of leafhoppers in the region this spring.

Their comparatively newer chemistry and selective mode of action make them valuable tools in Integrated Pest Management (IPM) programs. Similarly, Indoxacarb (37.5%), a sodium channel blocker, provided moderate control—supporting the findings of Abbas et al. (2014), who reported low to moderate resistance in *S. litura* populations from cotton fields of Pakistan.

Interestingly, Spinosad and Spinetoram (63.3%) also showed moderate efficacy, echoing the results of Ayyub et al. (2019), who tested spinosad in combination with a nuclear polyhedrosis virus and observed promising synergistic effects against *S. litura* larvae. However, the same authors and others such as Abbas et al. (2014) cautioned that spinosad resistance can evolve rapidly under continuous use. Methoxyfenozide (37.5%), another insect growth regulator, exhibited low control efficiency, possibly due to field resistance, as confirmed by Rehan et al. (2014), who documented the selection, cross-resistance, and stability of methoxyfenozide resistance in laboratory strains of *S. litura*.

The diamide group, represented by Flubendiamide (21.7%) and Chlorantraniliprole (17.5%), demonstrated notably low effectiveness in this dataset. Although these compounds initially revolutionized lepidopteran pest management due to their unique activation of ryanodine receptors, recent studies suggest emerging resistance in field populations. Ahmad et al. (2017) and Tong et al. (2013) both emphasized that frequent and repeated use of diamides without rotation has led to reduced susceptibility in *S. litura* and related species in South Asia.

The overall pattern of this study confirms what resistance monitoring programs have been warning about—no single insecticide remains permanently effective. Resistance levels vary widely among regions and cropping systems, shaped by local application practices and pest pressure. Hence, it is essential to rotate chemistries with different modes of action and to integrate biological control measures such as entomopathogenic nematodes or nuclear polyhedrosis virus. Khan et al. (2021) demonstrated that combining reduced-risk insecticides with biological agents provides additive effects and delays resistance buildup.

Conclusion and Recommendations

The general implication of the present study reflect that insect pest control in cotton is one of the top most challenging issue for maintaining production in Pakistan. Despite emergence of resistance and irrational use of insecticides, major pests namely whitefly, jassid, thrips, mealybug, dusky cotton bug, pink bollworms (PBW) spotted bollworms (SBW), American bollworm and armyworm remain posing serious threat to the crop yield. Even though newer chemistries, such as neonicotinoids, ketoenols, spinosyns and diamides have been successful for control in the recent past, resistance is reportedly on the rise in many of them also. Frequent reliance on the same classes of active ingredients, lack of rotation and insufficient adoption of biological versus cultural control techniques worsen resistance accumulation. Consequently, in spite of the complement C control being an indispensable tool for pest outbreak management; but exclusive reliance on pesticides has become impractical for long-term protection of cotton and environmental safety.

For the purposes of sustainable pest management, emphasis should be placed on implementation of integrated pest-management (IPM) approaches. Farmers should practice rotation of pest control materials, taking into account the mode of action of insecticides (6), apply chemicals only at an economic threshold level, and to use biological controls with their natural enemies such as predators and parasitoids. Resistant / tolerant varieties in the case of cotton also can reduce further pest pressure while use of cultural practices (timely sowing, field sanitation and crop rotation) can also bring about reduction in pest pressure. Furthermore, it is recommended that government extension agencies and private agribusinesses reinforce farmer education initiatives on pest recognition, judicious application of pesticides, and resistance management. There will be a need for continuous resistance monitoring at the local level and further development of new bio-rational insecticides to ensure long-term productivity and environmental sustainability in cotton.

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