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Review Article

Yield Decline and Resistance Development in Sucking Pests of Cotton in the Context of Unwise Spraying Techniques

Saleem Ashraf, Khalid Mahmood Ch., and Ijaz Ashraf*

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

Abstract: Over 100 countries are producing cotton, which provides raw materials to the industry and employment opportunities for the people. Limiting the cost of production, conserving the ecosystem, and improving the cotton yield are key ingredients of sustainable cotton production. The inception of transgenic cotton (Bt varieties) improved yields, curtailed pesticide uses and promoted environmental safety. Over the years, Bt varieties of cotton have lost resistance against bollworms, and yield is declining. Unwise application of pesticides is associated with the development of resistance to sucking pests of cotton. The present review was conducted to undertake (i) the background of cotton production in the world, (ii) varietal development in cotton, (iii) problems (increasing susceptibility) in Bt varieties (iv) reliance on pesticides, and (v) myths of pesticides applications followed by pesticides knowledge among farmers. The cotton varieties which are resistant against sucking pests should be introduced. In addition, the promotion of biopesticides and fostering the adoption of Integrated Pest Management Approaches could be effective for the management of sucking pests. Farmers must be trained in site-specific and accurate spraying techniques by agricultural extension and plant protection departments. Accurate spraying techniques will not only improve pest control but also help in curtailing the environmental pollution being caused by the excessive use of pesticides in cotton.

Keywords: Sucking Pests, Resistance, Susceptibility, Bollworms, Ecosystem, Biopesticides.

1. INTRODUCTION

The world is producing around 25 M tons of cotton. India, China, the United States, Pakistan, Brazil, Australia, Uzbekistan, Turkey, Turkmenistan and Burkina Faso are the top ten cotton-producing nations in the world [1]. Globally, the total cotton production was expected to reach 121.6 million bales in 2021-22 [2]. *Gossypium hirsutum*, *Gossypium babadense*, *Gossypium arboretum*, and *Gossypium herbaceum* are four commonly grown types of cotton. A major proportion of the cotton area is devoted to Bt cotton [3]. The global cotton production is forecasted to grow by 1.6% and reach 30.6 million tons by 2031. The average yield of cotton is also to grow at 1.3%, which is likely to back the increase in global production of cotton [4].

Cotton production is much needed for the world for many reasons, including an addition to the economy and support to livelihoods [5]. Conventional cotton was not very effective due to severe susceptibility to pests. Transgenic cotton helped to combat the pest's attack. Since the inception of transgenic cotton, pesticide use patterns have changed, production increased, and the natural enemy population jumped high, followed by improved land use efficiency and productivity [6]. However, transgenic cotton has started showing susceptibility towards pests; moreover, pests have developed resistance. This transition is not only decreasing production but also increasing the cost of pesticide application along with the occurrence of environmental degradation [7]. The improper application of pesticides seems more critical in developing resistance and leading transgenic cotton to failure.

With a population of over 212.82 million and a population growth rate of 2.4%, Pakistan is the 6th most populous nation. Agriculture contributes to 18.5% of the country's GDP and provides

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* Corresponding Author: Ijaz Ashraf <gilluaf707@uaf.edu.pk>

livelihood support to 38.5% of the population, making it a crucial sector for the country [8]. Cotton is one of the most significant crops produced in Pakistan. Cotton contributes to national economic development and for supporting the livelihoods of millions of farm families. Cotton has tremendous export potential, accounting for 55% of all foreign exchange incomes in Pakistan. Of the total farmers, 26% grow cotton in Pakistan, whereas 15% of the total cultivated area is devoted to cotton cultivation [9]. Approximately 65% of cotton is grown in Punjab province, which has arid conditions that are suitable for the crop. The remaining cotton is cultivated in Sindh, where the climatic conditions are relatively more humid [9]. Negligible areas in Khyber Pakhtunkhwa and Baluchistan are devoted to cotton. Cotton production contributes 4.5% of agriculture's value and 0.8% of the total GDP [10]. The area and production of selected countries using Bt varieties of cotton are presented in Figures 1 and 2. Figure 1 shows that the India, USA, Pakistan, China, Brazil and Australia are the leading countries in terms of cotton area devoted to Bt varieties of cotton [11]. Figure 2 shows that China, India, Pakistan, Brazil, Turkey and Uzbekistan were the top cotton-producing countries [12].

It is necessary to support cotton production, reduce the cost of production, improve quality, and implement policies to make farming profitable. Despite this, the agriculture sector has remained underdeveloped, and enhancing its performance is crucial for economic growth and poverty reduction. The present review is an integrated review to explore the cotton landscape in the world under prevailing conditions of Insect Pests and diseases. Effective management of insect pests is essential as they play a significant role in reducing the cotton yield. Over time, the insects' pests have gained resistance; this resistance is associated with the unwise application of chemicals. This review aimed to endorse accurate spraying techniques to manage the infestation of insect pests and conserve the ecosystem. This review was initiated from the (i) background of cotton production in the world, (ii) varietal development in cotton, (iii) problems (increasing susceptibility) in Bt varieties (iv) reliance on pesticides and (v) myths of pesticides applications followed by pesticides knowledge among farmers.

2. VARIETAL DEVELOPMENTS IN COTTON

2.1. Inception and Promotion of Bt Cotton

Conventional cotton was predominantly the critical choice of farmers before the inception of transgenic cotton. Over the period, traditional cotton was perceived as less effective for different reasons. Of the major reasons, low production was the foremost. Infestation of pests, especially armyworms, was intensive on conventional cotton, resulting in the high cost of production and exhibiting less production. Abro *et al*. [13] identified that cotton bollworms, mainly American, Pink, and Spotted bollworms, were the offensive pests, bringing around 30-40% yield loss. Farmers had to apply extensive chemicals to control the bollworms, which not only skyrocketed the cost of production but also accelerated the resistance of bollworms. PACRA [14] reported that during the fiscal year 2022, Pakistan imported pesticides worth USD ~201.7 mln, and ~69% of it was consumed on cotton crop only. In this context, conventional

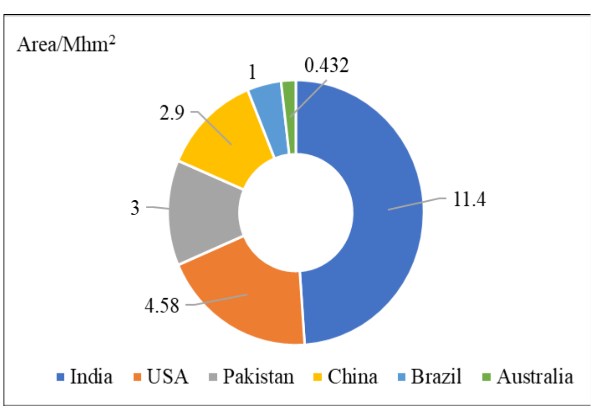

Fig. 1. Bt cotton cultivated area (Mh) in top cotton growing nations [11].

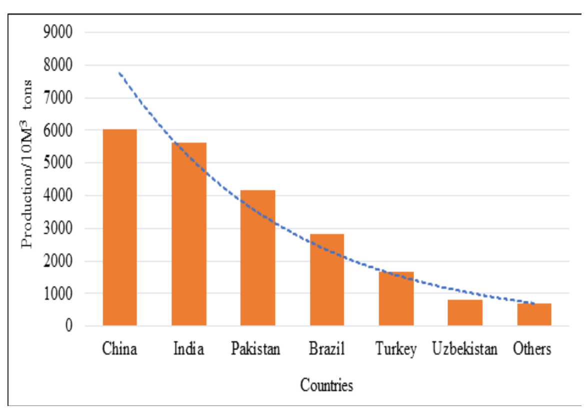

Fig. 2. Country-wise production of cotton in 2018-19 (1000 metric tons) [12].

cotton was deemed important for upgrading to new germplasms that are likely resistant to bollworms. The Pakistani government, in collaboration with the Center of Excellence in Molecular Biology (CEMB) and the National Institute for Biotechnology and Genetic Engineering (NIBGE), invested significant resources and human resources to develop genetically modified local varieties, specifically to tackle the issues in cotton production [15].

The first Bt variety of cotton was informally grown in Pakistan in 2002 [16]. However, the Bt variety obtained the final approval of the Government of Pakistan for cultivation in 2010. Contrary to Pakistan, the USA approved and commercialized the first Bt cotton variety in 1996 [17]. James [18] found that 12.1 million farmers had adopted GMO Genetically Modified Organisms) cotton, with the majority of them in China and India. In Pakistan, some private seed companies introduced the first Bt variety seed in the district Rahim Yar Khan [16]. The average yield of cotton in Pakistan was 0.5 t ha$^{-1,}$ considerably lower than the average yield achieved in China 9 t ha-1, indicating a wide yield gap in Pakistan [19]. The inception of the Bt variety was deemed important in bridging this yield gap of cotton prevailing in Pakistan [19]. The details of Bt and Non-Bt varieties approved in Pakistan from 2010-19 are tabulated in Table 1 [20].

2.2. Performance of Bt Varieties

Bt varieties were aimed at curtailing the undue application of pesticides and allowing growers to control insects and pests through minimum use of pesticides. Some benefits of Bt varieties are less attack of bollworms, minimum use of pesticides, high yield potential, and reduction in labour, which lure farmers to adopt Bt varieties over the non-Bt varieties [21]. Studies such as Qaim *et al*. [22], Bennett *et al*. [23], Subramanian and Qaim [24] and Kouser and Qaim [25] have confirmed that

Table 1. Bt and Non-Bt varieties approved in Pakistan from 2010-2019 (Adapted from Razzaq *et al.* [20]).

Sr. no.	Variety name	Year of release
	Bt varieties	
1	IR-3701	2010
2	Neelum-121	2010
3	FH-113	2010
4	Sitara-008	2010
5	MG-6	2010
6	Ali Akbar-703	2010
7	Ali Kabar-802	2010
8	IR-1524	2010
9	GN Hybrid-2085	2010
	Non-Bt varieties	
10	Sindh-1	2010
11	CRIS-342	2010
12	NIA-Ufaq-08	2010
13	Malmal	2010
	Bt varieties	
14	Tarzan-1	2012
15	MNH-886	2012
16	NS-141	2012
17	FH-114	2012
18	IR-NIBGE-3	2012
19	CIM-598	2012
20	Sitara 009	2012
21	A-One	2012
	Non-Bt varieties	
22	CIM-573	2012
23	FH-941	2012
24	FH-942	2012
25	GS-1	2013
	Bt varieties	
26	AGC-777	2015
27	MM-58	2015
28	LEADER-1	2015
29	VH-305	2015
30	IUB-13	2015
31	FH-LALAZAR	2015
32	BS-52	2015
33	BH-184	2015
34	Cyto-177	2015
35	AGC-999	2015
36	MNH-988	2015
	Non-Bt varieties	
37	Cyto-124	2015
38	NIAB-2008	2015
39	GOMAL-105	2015
	Bt varieties	
40	CIM-602	2016
	Non-Bt varieties	
41	NIAB-KIRAN	2016
42	CIM-620	2016
43	CRIS-129	2016
44	RJ-120	2016
	Bt varieties	
45	IR-NIBGE-4	2017
46	IR-NIBGE-6	2017
	Non-Bt varieties	
47	RH-668	2018
48	CIM-632	2018
49	NIAB-1048	2018
50	NIAB-545	2018
51	Crystal-12	2018
52	Sitara-15	2018
53	Sahara-150	2018
54	CIM-610	2018
55	RH-662	2018
56	FH-152	2018
57	FH-490	2019

with increased adoption of Bt cotton pesticide use decreased and cotton yield increased. As a result of the adoption of Bt varieties, not only was the use of pesticides reduced, but the cost of production also significantly declined, and the incidences of poisoning were reported to decrease [25]. USA [26], Mexico [27], South Africa [28], China [29], India [30] and Pakistan [21] have witnessed the benefits of Bt cotton, and its adoption was positive for the farmers for economic reasons as the yield was higher than the conventional cotton varieties [31]. Specifically, small farmers' yield increased due to Bt cotton adoption [32, 33]. Hofs *et al*. [34] reported that the economic returns of the Bt adoption were very bright, primarily due to a significant reduction in pyrethroid production. The overview of income benefits obtained from adopting Bt varieties is portrayed in Figure 3. This shows that India, China, USA, Pakistan, Brazil, Australia and Argentina were leading countries harvesting noteworthy income through genetically modified cotton [35].

3. PROBLEMS (INCREASING SUSCEPTIBILITY) IN BT VARIETIES

Bt varieties had resistance against the bollworms [13]. Despite its effectiveness, Bt cotton did not show high efficacy against insects that suck sap, such as whitefly, jassid, thrips, and mealybugs [36]. Dutt [37] reported a high infestation of mealybugs in Bt cotton varieties. Over time, Bt varieties are becoming vulnerable to pests and diseases, and their resistance is decreasing. Bt cotton contains a gene from the Bt bacterium that produces endotoxins harmful to certain Lepidopteran pests, including the Pink Bollworm [38]. However, the unforeseen return of key cotton pests that Bt was aimed to resist has augmented a new debate to rethink the resistance level of Bt cotton [39, 40]. Different pests attack Bt in various varieties, like different bollworms and whiteflies. In the subsequent section, debate is made about how bollworms, sucking pests, insects and viruses are influencing Bt varieties.

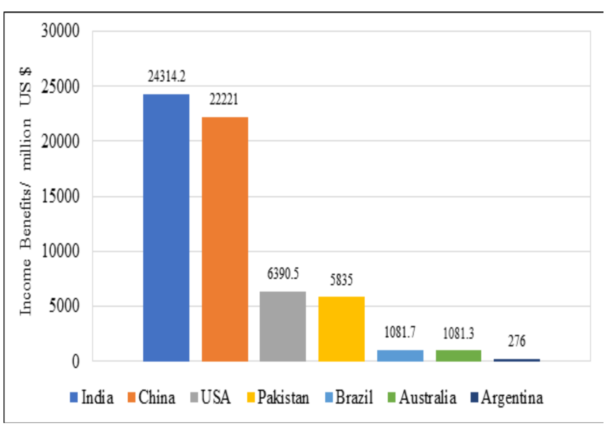

Fig. 3. Income benefits of genetically modified (GM) cotton farm in selected countries, 1996–2016 (million US$) [35].

3.1. Bollworms

Bt varieties have resistance against the bollworms, which were more hazardous in lowering the production and quality of cotton. Karar *et al*. [41] admitted that the risk of bollworms was significantly reduced in cotton after the introduction of Bt varieties. However, over the period, the resistance in Bt varieties decreased. Rabelo *et al*. [42], Zhang *et al*. [43] and Tabashnik *et al*. [44] reported that the Bt resistance against the bollworms was decreasing. The attack of Pink Bollworms on Bt cotton is more often visible [41]. Pink Bollworm (PBW) infestation on Bt varieties surprised the growers, and this attack caused a severe loss in yield and income [45]. The results of Rajput *et al*. [46] were confirmatory that PBW caused a reduction in the yield and caused damage to cotton lint quality, producing yellow spots on the fibre. This infected lint got lower rates in the market and significantly lowered the farmers' income.

PBW was also found to be responsible for delaying the maturity of cotton [47]. Studies were evident that PBW attacked all varieties of cotton. For instance, Gutierrez *et al*. [48] identified that PBW damaged the cotton crop grown in rain-fed condition and damage was relatively more serious as compared to the cotton grown in irrigated conditions. This damage was associated with climatic variations. However, they questioned the use and quality of Bt cotton seed and the number and quality of insecticides applied, especially in rainfed cotton. The findings of Lu *et al.* [49] were different to the studies conducted in Pakistan and India, as they found that Bt cotton varieties were effectively capable of controlling the population of bollworms in China. Resistance management methods are employed to control bollworms, significantly to alleviate the host plants and improve the resistance in Bt varieties. Rajapakse and Walter [50] found more attacks of bollworms in the cotton field as many weeds were growing around the field. In addition to field cleaning practices, the cultivation of natural refuge crops has been identified as a successful strategy to postpone the development of resistance to cotton bollworm [51]. It was recommended to grow non-Bt varieties alongside Bt varieties as a means of sufficiently delaying the development of bollworm resistance to Bt [52].

3.2. Cotton Leaf Curl Virus (CLCv)

The Gemini virus is responsible for causing Cotton Leaf Curl Disease (CLCv), which is a severe issue in cotton-producing regions worldwide. This virus spreads through the whitefly (*Bemisia tabaci*), and it can devastate the crop, leading to up to a 90% reduction in yield. This can also deteriorate the fibre quality [53]. The initial outbreak of CLCv was observed in Nigeria in 1912, and it has since spread to various cotton-producing countries, including the United States of America, Pakistan, India, and China [54]. Sattar *et al.* [55] argued that India and Pakistan were facing whitefly infestation in the cotton crop, resulting in losing the resistance. In 1989, CLCv was detected in the experimental fields of the Indian Agricultural Research Institute, New Delhi. Similarly, the existence of CLCv was later seen in Karnataka state, South India [56], and Northwest India in 1994 [57]. Specifically in Pakistan, the CLCv was first reported in Multan in 1967, and was perceived as a minor disease till 1987. However, it has spread over one million hectares of cotton area over the years as presented in Table 2 [58, 59]. CLCv damaged approximately 60% of the cotton crop in Multan in 1988, and the damage continues to occur each year. Pakistan and India have seen two epidemics of CLCv attack on cotton, causing a significant loss in production [55].

The incidences of CLCv are constantly changing over time, pointing towards the likely increase in yield decline [60]. CLCv grows in a suitable environment. Whitefly vectors can expedite the mode of spread [55]. The epidemiology of CLCv disease was related to abiotic factors like temperature and age of the plant [61]. Amrao *et al.* [62] found CLCv a very prominent disease. Around 70% of yield decline was witnessed subject to CLCv. The adverse impacts of the CLCv were more prominent on ginning out-turn and fibre fitness [63]. Nazeer *et al.* [64] stated that none of the varieties of *G. hirsutum* had resistance against the CLCv, although *G. Arboreum* has resistance against CLCv. In another study, Nawaz *et al.* [61] suggested changing the sowing times, cultural techniques, crop nutrition, buffer crops, whitefly

Table 2. Important landmarks in the history of CLCv. (Adapted from Rahman *et al*. [54]).

Year	History of CLCv
1912	• First report of CLCUD in Nigeria
1924	• Spread in Africa
1967	• CLCuD reported in Pakistan
1990	• First epidemic in Pakistan • Characterization of CLCuD initiated
1997-99	• Discovery of DNA alpha-satellite in 1999 • CIM-1100 was the first resistant variety followed by a number of varieties including CIM 448, CIM-496, NIBGE-2, FH-901, FH-1000, MNH-552, etc released in subsequent years
2001	• In 2001, CLCuBuV appeared in Pakistan • Beta-satellite discovered • DNA marker associated with resistance were identified
2005-10	• Antisense RNA, RNAi, etc has been utilized • Introgression breeding started • Release of tolerant cotton genotypes (NIBGE-115 and NN-3) • CLCuD reported in China
2012-13	• Dentification of asymptomatic cotton accession • Utilization in breeding as well as for DNA marker identification
2016	• Development of asymptomatic cotton lines • Identification of QTLs associated with diseases resistance

control and use of systemic chemicals followed by the seed treatment to manage the CLCv outbreak. Contrarily, late sowing of cotton, excessive use of nitrogenous fertilizer, and more attacks on insect pests exuberated the CLCv [65].

3.3. Sucking Insect Pests

Insects that suck sap, such as whitefly, thrips, and aphids, can be harmful to the health and productivity of cotton plants. Sucking insect pests have swapped the cotton bollworms. Since the inception of Bt varieties of cotton, about a 97% decrease in the chemical application was recorded. In the meantime, insecticides application jumped by 154% to control the sucking insect pests [66]. The overuse of insecticides had negative environmental consequences. Bt cotton varieties were not adequately resistant to insects that suck sap [67]. Therefore, continuously applying pesticides and insecticides is necessary to manage insect pests [34]. If pesticides are not appropriately applied, the population of insect pests multiplies, with significant inverse percussions on the crop [68].

Several studies like Abro *et al.* [13], Naveen *et al.* [69] and Sun *et al.* [70] augmented the higher infestation of sucking pests, including thrips, jassid, and whitefly, causing a significant decline in the cotton yield [71]. Jassid, thrip and Whitefly sucked the sap from the plant, turning the plant weak and ending in wilting and shedding of the leaves. These sucking pests have specific damage at the seedling stage of the crop and vegetative growth stage [13]. Whitefly further exaggerated the loss causing cotton leaf curl virus (CLCv) on cotton crops. India, one of the leading cotton producers, has reported a severe attack of whitefly on cotton during 2015-16 [69]. Sucking pests had a direct association with temperature and rainfall. Murtaza *et al.* [72] depicted that climate change had a significant impact on the population of sucking pests like Jassid. The findings of Harde *et al*. [73] confirmed that there was a positive correlation between the occurrence of sap-sucking pests such as whitefly, Jassid, Thrips, Mealybusg, and Aphid and the maximum temperature, minimum temperature, and maximum relative humidity. In another study, Shahid *et al.* [74] pointed out that the thrips and mites' population was high in June, August and September, augmenting the Jassid, whitefly and mealy bug population. This accentuates that with climate change, there are more chances of a high population of sucking pests. Therefore, with the increase in population, the chances of cotton yield losses will remain higher.

4. RESISTANCE DEVELOPMENT IN PESTS

Pertinent to increased resistance, the efficacy of Bt cotton varieties has declined [75]. Different factors contribute to the development of resistance to insect pests. Noncompliance with environmental protection agency regulations, inadequate production of high Bt endotoxins, repeated exposure to the same Bt endotoxins, and cross-resistance to multiple Bt endotoxins [76]. The variation in resistance of cotton armyworms and bollworms to insecticides was linked to the varying expression levels of Cry1Ac in the field conditions. This expression level was influenced by the plant's variety, age, and environmental factors [77, 78]. The resistance of insect pests was also found to increase due to insecticidal efficacy. The effectiveness of Bt varieties as insecticides was uneven due to the fluctuating expression of Bt protein throughout the cotton-growing season [79]. Insecticidal efficacy and ability were directly or indirectly predisposed by insect pests, disease intensity, rainfall amount, soil attributes, and apposite farm management. It can be deduced that an optimal environment was obligatory for Genetically Modified (GM) Cotton, which eventually reinforced the Bt gene expression. Huang *et al.* [76] specifically cited that in India, the development of resistance in pink bollworm (PBW) took seven years, which was attributed to the cultivation of unauthorized Bt cotton seeds. This resistance was associated with the low dose of Bt protein and non-compliance with the refuge strategy. Luo *et al.* [80] and Sethi and Dilawari [81] agreed that resistance in cotton insects and pests was due to the unwise application of pesticides on the crop. Sparks and Nauen [82] reported serious resistance in B. tabaci (whitefly), which is known for its enormous damage to the cotton crop in particular. The increased resistance in whiteflies has been reported in some countries [83, 84], and intensive pesticide use for insect and pest management inflated the infestation of whiteflies [85]. Ahmad *et al.* [63] reported a moderate resistance of whitefly against pyrethroids. It can be deduced that resistance to insect pests is increasing, and the unwise application of pesticides remains the critical reason.

4.1. Reliance on Pesticides Application

According to the report of Khan *et al.* [86], A total of 4875 kg of pesticide active ingredients were applied by farmers in the cotton belt of Punjab, Pakistan, per annum. The import of pesticides is also increasing each year [87]. Around 80% of all pesticides are used on cotton crops, while the remaining 20% are used on other crops like rice, sugarcane, maize, wheat, fruit orchards, and vegetables [87]. In the last 20 years, an expansion of 11.69% in the application of pesticides has been witnessed in Pakistan, and the total number of sprays per crop has reached more than 10 [88]. This extensive application is a point to ponder as human health is vulnerable to the impacts of chemicals, and insect pets have developed a high resistance level against the chemicals. No wonder the application of pesticides showed an increase in production by controlling the infestation of insect pests. From 1995 to 1998, an unexpected outbreak of insect pests caused a significant reduction in cotton yield from 849 to 230 kg/ha [89]. To combat this problem, the Government of Pakistan and pesticide manufacturers implemented a program involving increased pesticide use for monoculture crops. As a result, cotton production substantially increased from 2000 to 2001 [90]. The average yield in 1999-2000 reached 643 Kg/ha, from 494 Kg/ha, as recorded in 1997-98 and 1998-99. However, farmers in cotton-growing regions were applying 8 to 13 sprays per season and exceeding the recommended dosage to combat insect pests of cotton [91].

The extensive utilization of insecticides for managing whiteflies and other co-existing pests has resulted in a significant reduction of its natural enemies and the development of resistance to most of the conventional insecticides, thereby largely triggering whitefly outbreaks [63, 92]. According to the Central Cotton Research Institute (CCRI) in Multan, the two main cotton pests, the American bollworm and the whitefly, have developed resistance to commonly used pesticides [63, 92]. According to the Ministry of Food and Agriculture's report, there is evidence of a pesticide treadmill in Pakistan, as seen by the significant increase in applications of monocrotophos, cypermethrin, methamidophos, and dimethoate for controlling pests such as the American bollworm and whitefly. The application of monocrotophos has increased by 19 to 720 times, cypermethrin by 26 to 168-fold, methamidophos by 40 to 492-fold, and dimethoate by 104 to 725-fold to control these pests. Tariq *et al.* [91] indicated that before 1983, only a small percentage (5 to 10%) of cotton-growing regions in Punjab were treated with pesticides. However, this percentage increased to 100% by 1997. Overusing pesticides leads to insect pests developing resistance and poses a risk to farmers and community health. Excessive use of pesticides, such as spraying more than the recommended dose, in cotton fields poses a significant risk to field workers and pickers. It may result in unacceptable residue concentrations in cottonseed oil and cakes [90]. The discussion on the use of pesticides suggests that while their application has both positive and negative effects, the outcome depends largely on the spraying methods used by farmers. Further discussion on the various spraying techniques follows.

4.2. Myths of Spraying Techniques

Spraying techniques are of great worth in the wake of getting effective control over insect pests. In this regard, farmers use different spraying techniques. According to Tahir *et al.* [93], farmers typically use Knapsack and tractor-mounted boom sprayers to apply pesticides to crops in Pakistan. However, a significant issue with these sprayers is that the nozzle pressure is not consistently maintained during application, resulting in pesticide loss due to dribbling or drift. These problems increase production costs and contribute to environmental pollution and ecosystem imbalances. Damalas and Eleftherohorinos [94], most of the pesticides applied to the crops are wasted when they are used by farmers using improper techniques and nozzles. This wastage is an extra addition to the cost of production indeed.

Proper use of spraying techniques and nozzles greatly contributed to combatting insect pests. The type of nozzle, size, pressure on droplet size, and velocity are some aspects that farmers should consider palatably while spraying. The concerns made in this regard not only save the quantity of the pesticide but also curtail the cost of production [95]. Nozzles are classified based on droplet size and spray pattern [96]. Nozzles have three significant roles: breaking down the liquid into small droplets, dispersing these droplets in a specific pattern, and controlling the sprayer's release rate. Unfortunately, farmers have a poor understanding of nozzle function and often use too much or too little pesticide, leading to ecological disruption and pesticide waste [97]. Due to untrained pesticide applicators and faulty spray equipment, many pesticides sprayed on crops reach non-target areas [97]. Excessive use of pesticides can result in the death of unintended organisms, leading to the potential resurgence of insect pests [98]. Insecticides have become less effective against certain cotton pests, such as Heliothis and whitefly, due to the inappropriate use of pesticides [99, 100]. Ejaz *et al.* [101] augmented that approximately 50% of the pesticides applied to various crops are wasted on non-targeted areas, leading to increased production costs and environmental degradation of the surrounding soil, water, and air. This is mainly due to ineffective spraying machines that cannot maintain the specified nozzle pressure, discharge, and height, which impacts spray pattern, droplet size, and uniformity. The size of droplets can also affect the spray coverage, and as droplet size decreases, the potential for drift increases [102]. Klein *et al.* [103] pointed out that boom sprayers' non-uniform nozzle tip output resulted in a misapplication of pesticides. The components of a nozzle include a nozzle body, a strainer, a replaceable nozzle tip, and a cap for securing it. Although farmers in Iran have excessively used chemical pesticides, there is little comprehension of their criteria for selecting and utilizing pesticides [104]. Ensure the use of pesticides correctly by paying attention to the pressure and the spraying situation before application [105]. Improper use of spraying techniques harnesses its damage to human health as well. While developing countries use only 20% of the world's total pesticide volume, they suffer from disproportionately high pesticide poisoning rates [106]. This pity situation spotlights a dire need to combat the issue of improper handling and use of pesticides in the wake of effective ecosystem conservation and escalated knowledge levels to combat the issue of improper use of pesticides. In this regard, knowledge regarding pesticide application is regarded as mandatory.

4.3. Dilemmas of Pesticide Knowledge

Among various factors behind the ineffective use of spraying techniques and wastage of resources, inadequate knowledge on the part of farmers is more prominent. Knowledge and information about the appropriate use of pesticides are regarded as key to the effective use of pesticides [107, 108]. Farmers in Pakistan usually lack the knowledge to select appropriate pesticides and effective spraying techniques as per their needs. Allahyari *et al.* [109] reported that farmers moderately understood precise spraying techniques. Most of the farmers preferred pesticides that were easy to access from dealers and used in the field [110]. Ejaz *et al.* [101] reported a lack of knowledge regarding the detrimental consequences of pesticide exposure during pesticide application. Various researchers such as Lekei [111], Ngowi [112], Karamidehkordi and Hashemi [113] have reported that farmers' limited education levels and inadequate training of pesticide management have resulted in their insufficient knowledge about the appropriate use of pesticides in suitable amounts. Farmers had limited adoption of recommendations for the safe use of pesticides due to inadequate technical awareness and knowledge [114]. Farmers rely on traditional sources to acquire information rather than contacting technical institutions like plant protection and agriculture extension departments. Khan and Iqbal [115] reported farmers' over-reliance on fellow farmers for information as 70% of farmers obtained guidance on the safe use of pesticides from their fellow farmers. Rehman *et al.* [116] reported that fellow farmers were reported to be a primary source of guidance for selecting and using pesticides, including information on their proper handling and usage. In another study, Mubushar *et al.* [114] revealed that farmers were not firmly following the advice and recommendations disseminated by the extension field staff regarding the safe use of pesticides. The over-reliance of farmers on fellow farmers to acquire information has already been reported by various research studies such as Ashraf *et al.* [117] and Akinnagbe *et al.* [118].

5. IMPLICATIONS FOR THE WISE APPLICATION OF PESTICIDES AND INSECT PEST MANAGEMENT

Achieving higher production is the foremost concern for farmers and state institutions. For this reason, farmers implement whatever possible measure is needed. Among various options, the application of pesticides, insecticides and fungicides is perceived prominent as an infestation of insects, pests and diseases on crops not only significantly lower the level of production but also deteriorates the quality of produce. Tariq *et al.* [91] reported that a hefty pest attack during 1995-1998 reduced cotton production from 849 kg/ha to 230 kg/ha. Mealybug infestations in Pakistan was expected to decrease cotton yield by 1.3 million bales [119]. Mallah *et al.* [120] and Abbas *et al*. [121] reported a 20-40% loss in cotton production due to different insects and pets of the cotton. Around 24% of cotton production loss was due to jassid [20].

The implications for applying pesticides and insect pest management in cotton crop cultivation are paramount for ensuring sustainable and productive agriculture. Cotton, a major cash crop, is susceptible to various insect pests that can significantly impact yields if uncontrolled. Wise application of pesticides involves a judicious use of chemical agents, considering factors such as pest species, developmental stages, and potential ecological consequences. Wise application of pesticides in the cotton crop can reduce weed-related yield reduction by 50 to 85% and increase production costs by addressing labour shortages and labour wages [122]. Although farmers use various pest control methods to increase production and reduce yield loss, no single method of controlling insect pests is considered sufficient to achieve the desired production level. Using chemicals to protect crops is beneficial and an essential component of integrated pest management [123]. The integration of control measures can increase production significantly. If cotton pests are effectively controlled, the yield can be increased by 200-300 kg per hectare [124]. The government of Pakistan and pesticide manufacturers launched a program aimed at increasing the use of pesticides for monoculture crops. As a result, cotton production experienced a significant boost from 2000 to 2001 [89].

Integrated Pest Management (IPM) strategies, encompassing biological, cultural, and chemical control methods, emerge as a holistic approach to curb pest populations while minimizing environmental impact. Adopting IPM addresses immediate pest concerns and contributes to long-term pest resistance management, preserving the efficacy of available pesticides. Integrated pest management (IPM) in cotton crops can lead to long-lasting, economical, and eco-friendly benefits [125]. In a study, Kranthi and Russell [126] revealed that Integrated Pest Management (IPM) programs, using naturally occurring pest control components, result in favourable ecological, sociological, and environmental consequences for the cotton crop. The implications for the wise application of pesticides extend beyond pest control to broader environmental and economic dimensions. Overreliance on certain pesticides can lead to the development of resistant pest populations, necessitating a rotation of active ingredients to maintain efficacy. Moreover, indiscriminate pesticide use can adversely affect non-target organisms, soil health, and water quality [94]. A wise and informed approach involves selecting pesticides with lower environmental impact, adhering to recommended application rates, and incorporating non-chemical pest management methods whenever possible [127, 128]. Economically, the judicious use of pesticides minimizes production costs and conserves resources. By investing in research and extension services that promote wise pesticide application and integrated pest management, the agricultural sector can strike a balance between effective pest control, environmental stewardship, and economic sustainability in cotton cultivation [129]. Matteson [130] stated that Integrated pest management (IPM) extension education encourages wise pesticide use and empowers farmers to manage a healthy paddy ecosystem, promoting ecological balance in rice paddies. Improved agricultural extension services, such as the PlantWise program in China, lead to more sustainable pest management by increasing recommendations for biological control, pest monitoring, and cultural control [131]. Integrated pest management training in school extension programs effectively achieves sustainable agriculture [132]. Similarly, the Insecticide Resistance Management (IRM) program in India significantly improved farmers' knowledge in identifying insect pests, proper use of insecticides, and timely sowing of the cotton crop, but limited their understanding of cultural practices.

6. CONCLUSIONS AND RECOMMENDATIONS

Insect pests and diseases are key factors lowering the cotton yield. Insect pests in cotton crops are managed by applying various pesticides, which not only increase the cost of production but also contribute to environmental degradation. Over the years, insect pests have attained resistance against pesticides; even the resistance of the Bt gene has decreased being susceptible to bollworms (i.e. Pink Bollworm) and other sucking pests (i.e., whitefly). The unwise application of pesticides on cotton crops is the foremost reason for increasing resistance to insect pests. Cotton growers are usually unaware of the technical side of the spraying. Using traditional spraying methods was the ineffective and injudicious application of pesticides that caused environmental pollution. Farmers are deficient in technical knowledge about the safe application of pesticides. The deficiency of technical knowledge is also associated with reliance on traditional information sources (i.e., fellow farmers). Therefore, it is essential to improve farmers' technical knowledge of spraying techniques and curtail the cost of production. Helping farmers in pesticide selection, controlling overdosing/underdosing, and conserving the ecosystem, environment, soil and water should be priorities. Advisory service-providing institutions should technically guide the farmers regarding the safe use of pesticides. Developing trained and technically sound farmers who can serve as an information source for other farmers seems another vital avenue to consider. Moreover, there is a need for the development of sucking pest-resistant cotton varieties followed by the implementation of integrated pest management techniques.

6.1. Direction for Future Research

Based on this critical review, the following future research directions are proposed;

1. Future research could explore and evaluate alternative pest management strategies that reduce reliance on traditional spraying techniques. This might involve the assessment of biological control methods, such as the introduction of natural predators or the use of microbial agents to control sucking pests.
2. Research could focus on integrating precision farming technologies to optimize pesticide application in cotton fields. Precision agriculture tools, such as drone-based monitoring, satellite imaging, and sensor technologies, can potentially target pest-infested areas more precisely.
3. Understanding the factors influencing farmers' decision-making regarding pesticide use is crucial. Future research could delve into behavioural studies to explore the motivations, knowledge gaps, and perceptions contributing to unwise spraying techniques. Developing targeted educational interventions and extension programs to enhance farmers' understanding of pest management practices, including the consequences of unwise spraying, could be an effective strategy to address the issue.
4. To comprehensively address resistance development in sucking pests, a longitudinal study could be conducted to monitor resistance patterns over an extended period. This research would involve regular sampling and analysis of pest populations in cotton fields to track changes in resistance levels. Understanding the dynamics of resistance development over time could inform the development of more sustainable pest management strategies.

7. CONFLICT OF INTEREST

The authors declared no conflict of interest.

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