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Eco-epidemiology and climate-based IPM of pink bollworm (*Pectinophora gossypiella* Saunders) in cotton (*Gossypium hirsutum* L.) in farmer fields of Warangal, Telangana

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Abstract
Pink bollworm (*Pectinophora gossypiella* Saunders) remains a major pest in cotton (*Gossypium hirsutum* L.) cultivation in Warangal, India, causing considerable yield and economic losses. A three-year, multi-location study (2022-24) was conducted in farmer fields of Warangal district to assess seasonal pest dynamics, weather influence, and economic performance of Integrated Pest Management (IPM) compared with conventional Farmer Practice (FP). The IPM strategy, combining pheromone traps, cultural practices, biological agents (*Trichogramma chilonis*, *Beauveria bassiana*, neem oil), and need-based chemical sprays, consistently suppressed larval populations (7.0-7.8 larvae/50 bolls in peak month; overall 9.6-19.5) relative to FP plots (14.2-24.4 larvae/50 bolls), reduced rosette flower incidence (2.8-8.5% vs 6.1-26.9%), and minimized green boll damage (2.0-7.5% vs 15-21%). Peak PBW activity occurred in October during boll formation, followed by a rapid decline. Pearson correlation and multiple regression analyses identified rainfall as the principal inhibitory factor (r = -0.70), while temperature and sunshine hours moderately favored larval development; the regression model explained 72% of variability in IPM plots. IPM interventions increased cotton yield by 43.5-57.3% (30.5-35.0 q/ha), improved net returns (₹124,715-172,450/ha), and achieved higher benefit-cost ratios (2.72-2.90:1) than FP. Technology Index and Technology Achievement Index trends indicated enhanced adoption and efficiency of IPM practices. Overall, climate-responsive IPM effectively suppressed PBW, improved productivity and profitability, and provides a sustainable, eco-friendly strategy for cotton cultivation in Warangal, India.

Keywords: Cotton, *Pectinophora gossypiella*, integrated pest management, seasonal incidence, weather correlation, technology adoption, yield, economics

Introduction
Cotton (*Gossypium hirsutum* L.) is a vital cash and fiber crop in India, supporting the livelihoods of millions of smallholder farmers (Kumar *et al*., 2025) [3]. However, the productivity of cotton in Telangana, Warangal has been increasingly threatened by the pink bollworm (*Pectinophora gossypiella* Saunders), a persistent pest responsible for severe yield reduction and fiber quality deterioration (Sharma and Singh, 2023) [11]. Despite the adoption of Bt cotton, resurgence of PBW infestations has been widely reported across India due to the evolution of resistance and reliance on calendar-based pesticide applications (Fand, 2021) [1]. As of the 2023-24, Telangana produced approximately 5.08 million bales of cotton, ranking it as the third-largest cotton producer in India, following Gujarat and Maharashtra. In Warangal, cotton is cultivated about 1.22 lakh acres, with yield of 7.34 lakh quintals for the year 2023-24 (PJTSAU Cotton Outlook, 2024) [8]. Integrated Pest Management (IPM) provides a scientifically validated and eco-friendly approach (Khan and Khan, 2021) [2]. Its effectiveness is influenced by climatic factors such as temperature, rainfall and sunshine, which affect PBW development and crop damage (Sambasiva Rao *et al.*, 2023) [10]. In Telangana, fluctuating weather strongly impacts PBW population dynamics and infestation patterns. Although IPM has proven effective in Warangal, detailed analyses of pest-weather interactions and technology adoption remain limited (Rajashekhar *et al.*, 2024) [9].

This study aimed to examine the influence of weather on PBW under IPM and Farmer Practice (FP) systems and evaluate effects on cotton yield, economic returns and technology adoption.

Materials and Methods

Study Area and Experimental Design

The field experiment was conducted in farmer fields across Warangal district (17.9693° N, 79.5926° E), Telangana, India, characterized by a semi-arid tropical climate with an annual rainfall 955 mm. A paired-plot design was employed, consisting of IPM demonstration plots and adjacent Farmer Practice (FP) plots with 0.4 ha. Each treatment was replicated across 20 locations. Private Bt cotton hybrids (farmer interested) of similar maturity duration were sown during late August under recommended agronomic practices, ensuring uniform crop establishment and management.

Treatments and IPM Components

The IPM module implemented a holistic combination of ecological, biological and chemical tactics to sustainably manage PBW infestation. Each plot was equipped with pheromone traps at 8/acre for monitoring and mass trapping of adult moths, with economic threshold levels defined as 8 moths per trap per day or 10% rosette flowers or 10% bolls, facilitating timely decision-making. Cultural practices, including incorporation of stubbles, summer ploughings, removal of rosette flowers, and destruction of infested fruiting bodies, were implemented before flowering to reduce pest carryover. Biological control was achieved through the release of *Trichogramma chilonis* (50,000 adults/ha) at 15-day intervals from flowering to boll formation to parasitize PBW eggs, while bio-pesticides such as *Beauveria bassiana* (5 g/L) and neem oil (1500 ppm @ 5 ml/L) were applied during early infestation stages immediately after egg laying. Need-based chemical interventions were applied when ETL was exceeded and included azadirachtin (1500 ppm) @ 5 ml/L with Sandovit 1 ml/L, profenophos @ 2 ml/L, emamectin benzoate @ 0.5 g/L, and profenophos + cypermethrin @ 2 ml/L, applied during peak larval activity or upon detection of damage in rosette flowers or bolls. In contrast FP plots relied on conventional calendar-based insecticide schedules without pheromone monitoring or biological interventions, often resulting in higher pest pressure and lower cost-effectiveness.

Data Collection and Observations

Observations were recorded fortnightly from September (standard week 36) to December (week 50) to monitor the seasonal incidence and crop damage caused by PBW. In each plot, 50 plants were randomly selected to record key pest parameters. The rosette flower infestation were calculated as the number of rosette flowers per 100 total flowers, whereas the larval population was determined based on the number of PBW larvae per 50 randomly selected green bolls from selected plants. Similarly, green boll and locule damage percentages were estimated from 100 sampled bolls and locules, respectively. In addition to field observations, fortnightly meteorological data including mean maximum and minimum temperatures, rainfall, and sunshine hours were obtained from the Telangana Development Planning Society (TGDPS), 2024 to analyze weather-pest relationships and temporal variability.

Statistical and Economic Analysis

"Pearson's correlation" coefficients were computed to determine the relationships between PBW infestation parameters and prevailing weather variables. Multiple linear regression analysis was employed to quantify the combined effects of meteorological factors on larval population dynamics, with the coefficient of determination (R^2) indicating model accuracy. Economic evaluation involved the computation of gross and net returns and benefit-cost (B:C) ratios based on prevailing market prices and input costs. The Technology Gap, Extension Gap, Technology Index and Technology Achievement Index (TAI) were estimated following the methodology of Rajashekhar *et al.*, (2024) [9].

Results and Discussion

Seasonal Incidence of Pink Bollworm (PBW)

The seasonal incidence of pink bollworm (PBW), including larval development, rosette flower incidence, and green boll damage under both Integrated Pest Management (IPM) and Farmer Practice (FP) were presented in Table 1 and Figure 1. These observations demonstrated the effectiveness of IPM in suppressing PBW and minimizing yield losses throughout the cropping season.

Rosette Flower and Larval Incidence

The percentage of rosette flowers in IPM plots remained consistently lower than in Farmer Practice (FP) plots throughout the cropping season. In September, IPM plots recorded 6.5-7.2%, compared with 20.2-24.4% in FP. Peak incidence was observed in October, with IPM plots at 8.2-8.5% versus 23.7-26.9% in FP. By December, rosette flowers declined to 2.8-4.5% in IPM and 6.1-10.1% in FP. The difference between IPM and FP was statistically significant (CD 0.9-1.8, $p<0.05$), indicating that early IPM interventions effectively reduced flower malformation caused by PBW. The low SD (0.3-0.9) and SEM (0.28-0.6) values suggest minimal variability among replicate plots, confirming consistency of IPM effectiveness across locations. Larval counts in IPM plots were maintained below 10 larvae per 50 bolls at all observation periods, whereas FP plots recorded significantly higher populations (14.2-24.4 larvae/50 bolls). Peak larval activity occurred in October (IPM: 7.0-7.8; FP: 22.6-24.4). Statistical analysis indicated significant suppression of larvae under IPM (CD = 0.8-1.7, $p<0.05$). The low SD (0.3-0.8) demonstrates uniform pest suppression across sites, emphasizing the reliability of IPM interventions such as pheromone trapping, biological control, and selective insecticide use.

Green Boll and Locule Damage

Green boll damage in IPM plots remained below 8%, while FP plots suffered 15-21% damage. Similarly, green locule damage in IPM plots ranged from 2.0-5.0%, significantly lower than FP (5.15-28.2%). Differences were statistically significant across all weeks (CD=0.7-1.5, $p<0.05$), and the low SEM indicates minimal experimental error. These results highlight the combined effect of IPM components in reducing fruit damage and preventing yield loss.

The study demonstrated that Integrated Pest Management (IPM) significantly suppressed pink bollworm (PBW) infestation and minimized crop damage compared with Farmer Practice (FP). Rosette flower incidence in IPM plots remained consistently lower throughout the season, ranging from 2.8-8.5%, while FP plots recorded 6.1-26.9%, highlighting the effectiveness of early-season interventions such as pheromone traps and biological control; similar reductions have been reported by Likhitha *et al*. (2021). Larval populations in IPM plots were maintained below 10 larvae per 50 bolls, whereas FP plots reached 24.4 larvae per 50 bolls, consistent with observations by Nagrare *et al.* (2025) [6], emphasizing the role of integrated strategies in limiting pest buildup. Green boll and locule damage was also substantially reduced under IPM (2.0-7.5% and 3.5-5.5%, respectively) compared to FP (15-21% and 5.15-28.2%), aligning with the findings of Rajashekhar *et al.* (2024) [9], which confirmed that IPM reduces fruit damage and yield loss.

Table 1: Seasonal dynamics and damage of pink bollworm (*Pectinophora gossypiella* Saunders) in cotton under IPM and farmer practice (2022-2024)

Month(s)	Standard week	Rosette flower (%)		No. of larvae/50 bolls		Green boll damage (%)		Green locule damage (%)	
		IPM Demo	FP	IPM Demo	FP	IPM Demo	FP	IPM Demo	FP
September	36	6.5±0.8	20.21±1.2	4.5±0.5	19.50±1.1	5.0±0.6	15.55±1.0	2.5±0.4	7.00±0.7
September	38	7.2±0.7	24.43±1.3	5.8±0.6	21.60±1.2	6.0±0.7	17.20±1.1	2.8±0.5	7.05±0.6
October	40	8.5±0.9	23.71±1.4	7.0±0.7	24.40±1.3	7.5±0.8	20.20±1.2	3.0±0.6	6.15±0.5
October	42	8.2±0.8	26.91±1.5	7.8±0.8	22.60±1.2	8.0±0.9	21.10±1.3	3.5±0.7	8.75±0.6
Oct/Nov	44	7.5±0.7	18.84±1.1	6.5±0.6	24.00±1.3	6.8±0.7	20.85±1.2	3.8±0.6	10.45±0.7
November	46	6.0±0.6	17.39±1.0	6.0±0.6	23.55±1.2	7.5±0.8	21.00±1.3	4.0±0.7	12.70±0.8
Nov/Dec	48	5.0±0.5	17.25±1.0	5.8±0.6	22.45±1.2	6.0±0.7	20.35±1.2	5.0±0.8	28.20±1.5
December	50	4.5±0.4	10.12±0.8	5.0±0.5	14.21±1.0	5.5±0.6	12.80±0.9	3.5±0.6	16.30±1.1
December	52	2.8±0.3	6.12±0.6	2.5±0.3	3.23±0.5	3.0±0.4	4.75±0.6	2.0±0.3	5.15±0.5
Means		5.91±0.7	18.33±1.2	5.66±0.6	19.50±1.2	6.05±0.7	17.09±1.2	3.61±0.5	11.31±0.8
CD (5%)		0.9	1.8	0.8	1.7	0.9	1.6	0.7	1.5
SEM		0.3	0.6	0.28	0.57	0.29	0.53	0.23	0.5

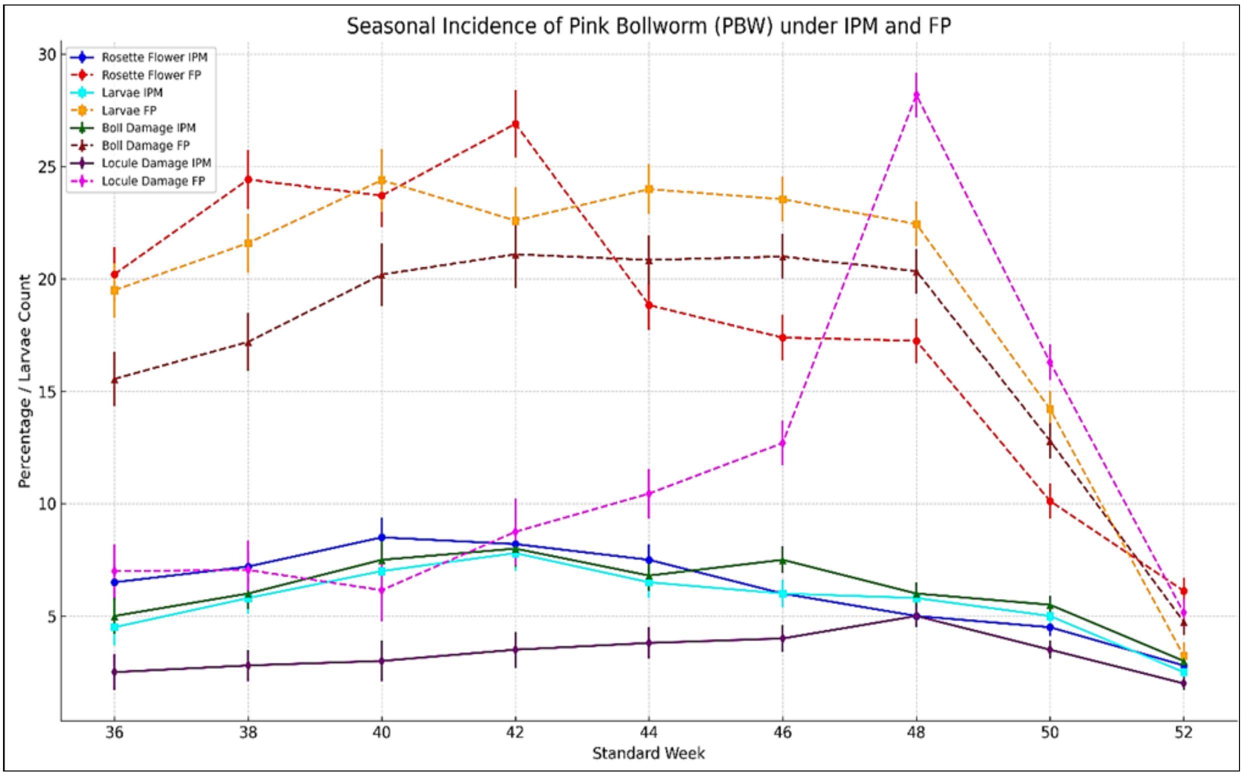

Fig 1: Pooled seasonal trends of pink bollworm infestation and damage in cotton under IPM Demonstration vs Farmer Practice

Influence of weather parameters on PBW Development

The impact of weather parameters on PBW is illustrated in Figure 2 (correlation) and Table 2 (regression), with regression lines in Figure 3.

Correlation and Regression Analysis

Pearson correlation revealed that rainfall was strongly negatively correlated with larval populations (IPM: r = -0.70; FP: r = -0.60), indicating suppression of PBW activity. Average high and low temperatures were positively correlated (IPM: r = +0.62 and +0.68; FP: r = +0.44 and +0.38), suggesting that warmer conditions favored larval development. Sunshine hours showed weak positive correlations (IPM: r = +0.45; FP: r = +0.38). Green boll and locule damage followed similar patterns, with lower damage under IPM. Multiple regression confirmed rainfall as the primary suppressive factor, while temperature and sunshine had secondary positive effects. The models explained 72% of variability in IPM plots ($R^2 = 0.72$) and 61% in FP plots ($R^2 = 0.61$). Negative rainfall coefficients confirmed its inhibitory effect, whereas positive temperature coefficients indicated enhanced larval activity under warmer conditions. Predicted larval counts closely matched observed values in IPM plots, while FP plots showed greater variability.

Weather parameters strongly influenced PBW activity; rainfall was negatively correlated with larval populations (IPM: r = -0.70; FP: r = -0.60), indicating suppression of pest activity during wet periods, in agreement with Patel *et al.* (2025) [7]. Conversely, higher temperatures were positively correlated with larval populations, suggesting warmer conditions favor PBW development, consistent with Fand (2021) [1]. Sunshine hours showed a weaker positive correlation, indicating limited influence on larval activity. Multiple regression analysis confirmed rainfall as the primary suppressive factor, while temperature and sunshine had secondary effects, explaining 72% of variability in IPM and 61% in FP plots, reinforcing the value of weather-informed pest management.

Table 2: Comparative regression of PBW larval populations in cotton under IPM demonstration and farmer practice, Warangal

Dependent Variable	Intervention	Independent Variable	Coefficient (β)	Std. Error	T-Value	P-Value
Larvae	IPM (Demo)	Intercept	-5.23	4.50	-1.16	0.30
		Avg high (°C)	0.85	0.42	2.02	0.09
		Avg low (°C)	0.32	0.31	1.03	0.35
		Rainfall (mm)	-0.28	0.08	-3.50	0.01*
		Sunshine hours	0.12	0.10	1.20	0.27
	FP	Intercept	-3.10	5.0	-0.62	0.55
		Avg high (°C)	0.55	0.50	1.10	0.32
		Avg low (°C)	0.21	0.35	0.60	0.57

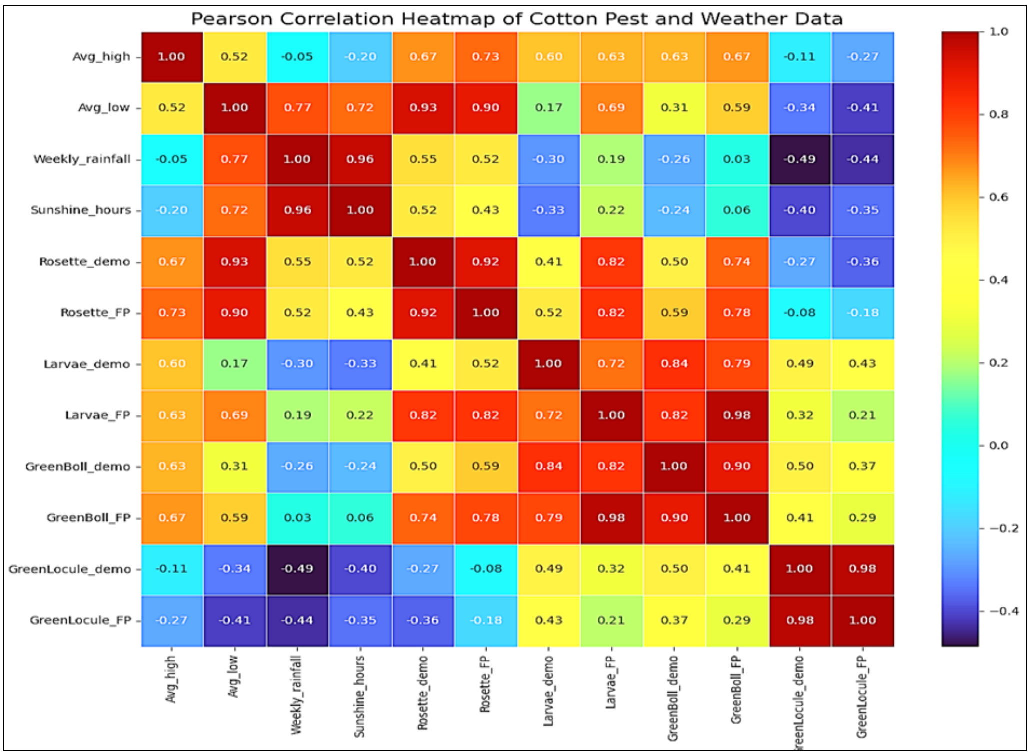

Fig 2: Heatmap of correlations between PBW larval density and climatic parameters in cotton under IPM and FP, 2022-2024

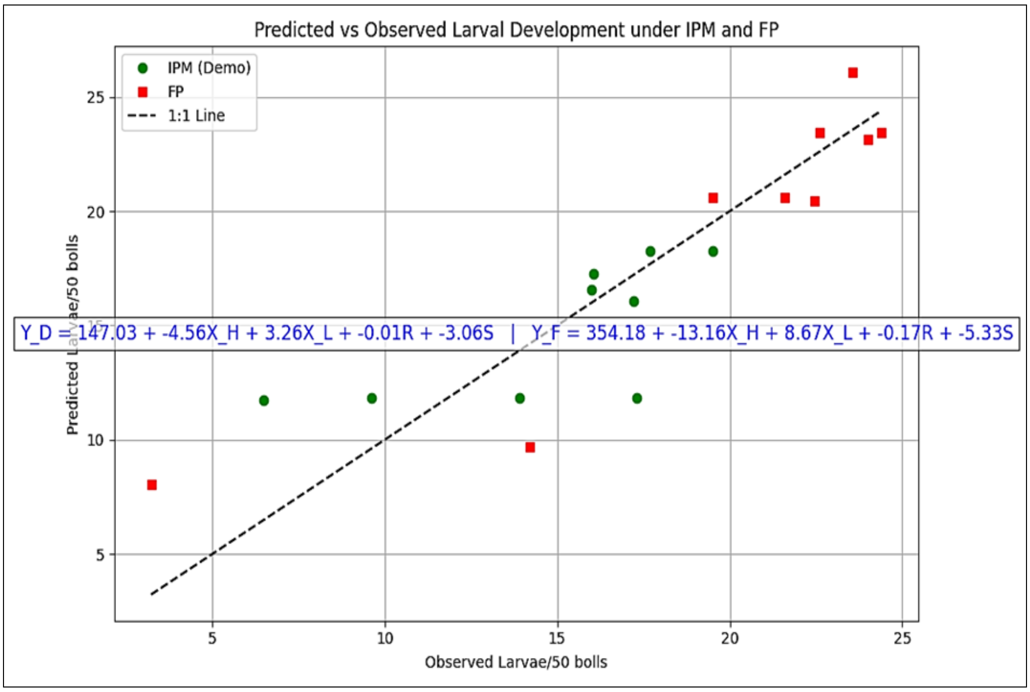

Fig 3: Regression analysis of pink bollworm larval population under IPM and farmer practice in cotton, Warangal (2022-2024)

Yield, Economics and Other Extension Parameters

Yield, economic returns and extension parameters were summarized in Table 3 and Figure 4. IPM plots recorded 30.5-35.0 q/ha, while FP plots produced 21.3-22.3 q/ha, representing a 43.5-57.3% yield increase under IPM. Net returns were higher in IPM (Rs. 124,715-172,450/ha) than FP (Rs. 51,325-72,320/ha). B:C ratios under IPM (2.72-2.90:1) exceeded FP (1.61-1.76:1), reflecting better profitability despite slightly higher input costs. The Technology Index declined from 15.3% (2022-23) to 2.8% (2024-25), indicating improved efficiency and adoption. The Technology Gap decreased from 5.5 to 1 q/ha, while the Extension Gap rose slightly (9.3-12.8 q/ha), suggesting room for broader adoption. The Technology Achievement Index (TAI) increased from 62.7% to 92.7%, confirming progressive adoption of IPM practices. The bar-and-line graph (Figure 4) illustrated superior performance under IPM in terms of yield, efficiency, and technology adoption, with moderate extension gaps indicating potential for enhanced farmer training.

In terms of productivity and economics, IPM plots yielded 30.5-35.0 q/ha compared to 21.3-22.3 q/ha in FP, resulting in a 43.5-57.3% increase in yield, supporting findings of Nagrare *et al.* (2023) and Sharma and Singh (2023) [11] who reported higher yields under IPM. Net returns were also higher under IPM (Rs. 124,715-172,450/ha) compared to FP (Rs. 51,325-72,320/ha), with Benefit-Cost ratios of 2.72-2.90:1 versus 1.61-1.76:1, highlighting the economic viability of IPM interventions. Technology adoption improved over the three-year period, with the Technology Achievement Index rising from 62.7% to 92.7%, consistent with Gohil (2016), although moderate Extension Gaps (9.3-12.8 q/ha) indicate ongoing need for farmer training. Overall, the study confirms that IPM effectively reduces rosette flower incidence, larval populations, and boll/locule damage, while improving yield, profitability, and technology adoption under farmer fields of Warangal district.

Table 3: Impact of IPM and farmer practice on cotton (*Gossypium hirsutum* L.): damage, yield, and technology indices (2022-2024)

Parameter	2022		2023		2024		Pooled	
	IPM	FP	IPM	FP	IPM	FP	IPM	FP
Rosette flowers (%)	13.9	18	13.7	18.4	13	18.6	13.6	18.3
No of larvae/50 bolls	15	19.2	14.9	19.5	14.7	19.8	14.9	19.5
Green boll damage (%)	15.6	16.8	15.2	17.1	14.7	17.3	15.2	17.1
Green locule damage (%)	9	11.2	8.9	11.3	8.8	11.4	8.9	11.3
Yield (q/ha)	30.5	21.3	32.5	22	35	22.3	32.7	21.8
Cost of cultivation (Rs./ha)	69,875	84,250	83,750	89,750	90,750	95,000	74,125	86,333
Gross returns (Rs./ha)	194,590	135,575	228,150	154,440	263,200	167,320	228,647	152,445
Net returns (Rs./ha)	124,715	51,325	144,400	64,690	172,450	72,320	154,522	66,112
B:C ratio	2.79:1	1.61:1	2.72:1	1.72:1	2.90:1	1.76:1	2.88:1	1.77:1
Percent increase yield over FP (%)	43.5	–	47.7	–	57.3	–	49.6	–
Technology Index (%)	15.3	–	9.7	–	2.8	–	9.3	–
Technology Gap (q/ha)	5.5	–	3.5	–	1	–	3.3	–
Technology Achievement Index (%)	62.7	–	75	–	92.7	–	76.5	–
Extension Gap (q/ha)	9.3	–	10.5	–	12.8	–	10.8	–
Technology Adoption (%)	85	–	88	–	90	–	88	–

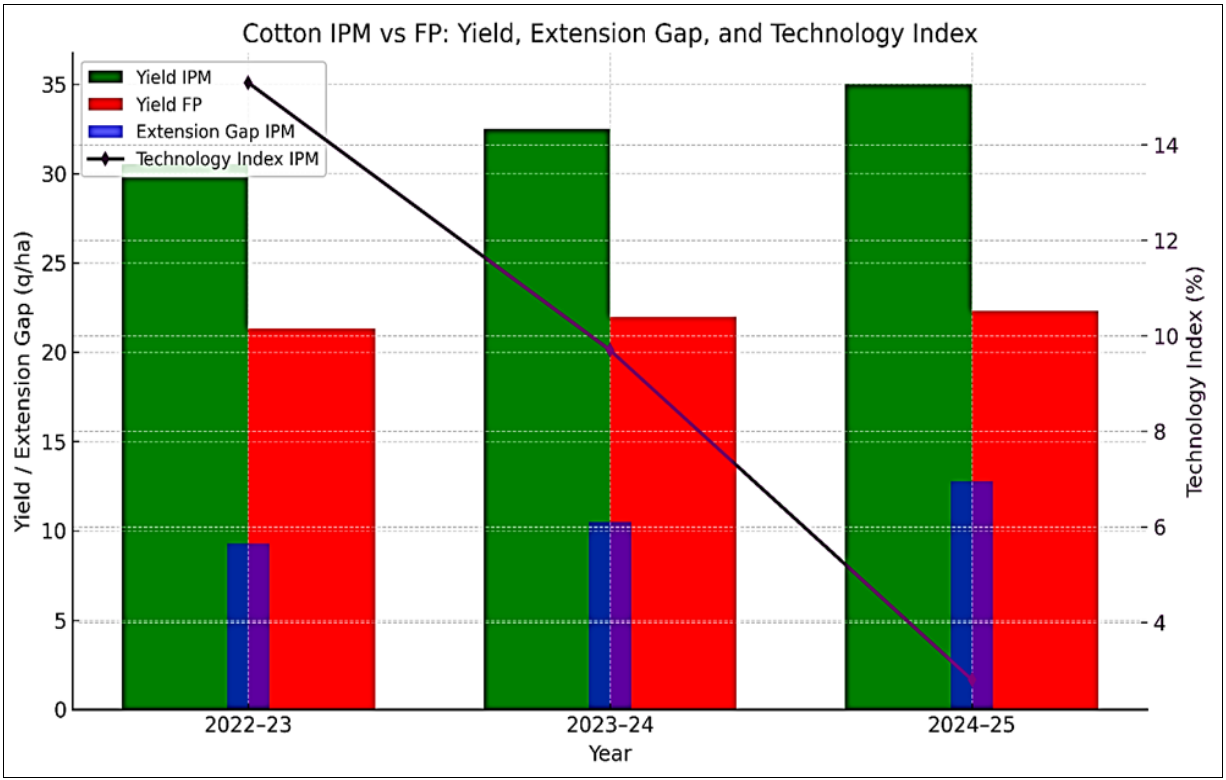

Fig 4: Cotton yield and extension gap with technology index under IPM and FP for 2022-2024

Conclusion
Integrated Pest Management (IPM) consistently maintained lower PBW infestation than Farmer Practice (FP), reducing larval populations, rosette flower incidence, and locule damage throughout the crop cycle. Peak PBW activity occurred in October, declining sharply thereafter. Rainfall was the primary suppressive factor, while temperature and sunshine moderately promoted larval activity. Weather-based forecasting explained 72% of larval variability in IPM and 61% in FP plots, supporting its use in timing interventions. IPM enhanced yield, profitability, and fiber quality, reduced pesticide use, and improved technology adoption. To ensure widespread impact, continued farmer training, extension support, and identification of adoption barriers are essential. Overall, IPM represents a sustainable, eco-friendly, and economically viable approach to PBW management in semi-arid cotton ecosystems.

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Ethical Approval
Not applicable. This study did not involve any human or animal subjects requiring ethical clearance.

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