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RESEARCH ARTICLE

Insecticidal longevity and resistance trends in cauliflower pests: A survival analysis approach

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Abstract

Survival analysis is widely used to evaluate the effectiveness of insecticide trials on insect survival, which can also be used to estimate the durability of insecticides. This study focuses on the major pests of cauliflower that are capable of causing significant damage. Depending on the pest species and their population density, these infestations can lead to yield losses of up to 100 %. Major pest species in cauliflower are generally assumed to develop resistance more rapidly than minor pests. However, few studies have systematically analyzed published resistance data to compare resistance development among different species. Using 412 records from the Arthropod Pesticide Resistance Database covering 16 species, this study applied survival analysis to estimate the number of generations required for resistance to emerge following insecticide introduction. The results revealed significant variation among species in resistance development rates. On average, resistance first appeared after 178 generations in tropical regions and 56.5 generations in temperate regions. Insecticide durability also varied by Mode of Action (MoA) and year of introduction. On average, insecticides remained effective for 184.6 generations in tropical regions and 54.73 generations in temperate regions. For Diamondback moth control, estimated longevity in tropical regions was 7 years for Diamides, 8.5 years for Spinosyns and 12.9 years for Milbemycins. In temperate regions, effectiveness was estimated at 7 years for Diamides, 9.75 years for Spinosyns and 18.75 years for Milbemycins. Unlike traditional methods that depend on periodic field surveys or lab tests, survival analysis uses time-based data, including censored information, to give more reliable and consistent estimates of how quickly resistance develops and how long insecticides remain effective across different pests and modes of action.

Keywords: insecticide resistance; Kaplan-Meier estimator; log-rank test; Mode of Action; phylogenetic pests; time-to-event analysis

Introduction

Cauliflower (*Brassica oleracea* var. *botrytis*), a commercially significant vegetable crop of the Brassicaceae family, is extensively cultivated in various regions, including India, China, Italy, Europe and North America (1, 2). China is the leading global producer, with an annual yield exceeding 9 mmt, followed by India, which produces over 8.5 mmt of fresh cauliflower curd each year (3). However, cauliflower cultivation is adversely affected by insect pests, with a total of 24 species documented in the cauliflower agroecosystem throughout the cropping period. The primary insect pests infesting cauliflower include the diamondback moth (*Plutella xylostella*), cabbage webworm (*Hellula undalis*), cabbage white butterfly (*Pieris brassicae*), cabbage aphid (*Brevicoryne brassicae*), cabbage looper (*Trichoplusia ni*) and green peach aphid (*Myzus persicae*) (4). Additionally, other significant pests such as the tobacco cutworm (*Spodoptera litura*), cabbage stem flea beetle (*Psylliodes chrysocephala*), western flower thrips (*Frankliniella occidentalis*), corn earworm (*Helicoverpa zea*) and beet armyworm (*Spodoptera exigua*) also contribute to yield reductions in cauliflower. These pests can cause significant damage, with severe infestations resulting in yield losses of up to 31-100 %, depending on the species and their population density (5).

The development of insect resistance to insecticides presents a significant challenge to effective pest management, resulting in substantial agricultural and economic losses (6). Field-evolved resistance occurs when repeated exposure to a pesticide causes a population to become less susceptible due to genetic changes (7). While individual case studies have helped us to understand specific instances of resistance, the overall evolutionary patterns behind this process remain unclear (8). For example, some species seem to develop resistance faster than others, but this idea is mostly based on observations rather than statistical analysis. By studying data across different insecticides and species, researchers may be able to uncover patterns in how resistance develops, which could help create better strategies to slow its spread.

Insect pests develop resistance to insecticides through multiple mechanisms. Metabolic detoxification involves the enzymatic breakdown of insecticides by detoxifying enzymes such as cytochrome P450 monooxygenases, glutathione S-transferases (GSTs), esterases, carboxylesterases, UDP-glycosyltransferases (UGTs), aldehyde oxidases, sulfotransferases and multidrug resistance-associated proteins (MRPs) (9, 10). Target-site resistance arises due to the genetic mutations that modify the binding sites of insecticides, rendering them ineffective. Behavioural resistance enables pests to mitigate exposure by exhibiting avoidance behaviours, including reduced contact with treated surfaces, decreased feeding, evasion of treated areas, increased grooming to remove insecticidal residues and temporal shifts in activity patterns. Additionally, cuticular resistance, characterized by cuticle thickening, reduces insecticide penetration, further enhancing resistance (11, 12). Cross-resistance enables insect populations to develop resistance to multiple insecticides with similar Mode of Action (MoA), further complicating pest management. These adaptive mechanisms pose significant challenges, necessitating the implementation of integrated pest management (IPM) strategies to delay resistance development and preserve insecticide efficacy. However, comprehensive comparative analyses across different geographic regions and pesticide classes remain limited in the existing literature. The adaptive potential of pest species is considered a key determinant of this variation, as certain species exhibit a higher capacity for rapid adaptation and resistance development compared to others.

To enhance the understanding of variations in insecticide resistance development and the durability of insecticide efficacy, Survival Analysis (SA) serves as a valuable statistical tool (13, 14). SA, also referred to as time-to-event analysis, comprises a set of statistical techniques designed to estimate the distribution of outcome variables that are subject to censoring, truncation, or both (15, 16). It is particularly advantageous for examining time-dependent processes, such as the duration of insecticide effectiveness before resistance emerges. SA enables the estimation of hazard functions, median survival times and comparisons of survival distributions across different insecticide treatments. Additionally, it accounts for right-censored data, where the precise time of resistance onset is not observed for all cases. Advanced modeling approaches, including the Cox proportional hazards model and parametric methods such as the Weibull, exponential and log-normal models, facilitate the quantification of factors influencing insecticide durability. By integrating these methodologies, SA provides a robust analytical framework for predicting resistance evolution and optimizing sustainable pest management strategies.

Survival Analysis (SA) is widely utilized in medical research to evaluate patient outcomes, including survival probabilities in conditions such as breast cancer (17), metastatic colorectal cancer (18), uterine carcinosarcoma (19) and heart transplants following Fontan failure (20). In the field of entomology, SA has been applied to investigate various aspects of insect survival, such as the mortality of *Popillia japonica* following insecticide exposure (14), the lifespan of mosquitoes infected with the dengue virus (21) and the impact of temperature on species including *Spodoptera exigua*, *Monolepta hieroglyphica* and *Chrysoperla externa* (22-24). In agriculture and pest management, SA serves as a critical tool for assessing the efficacy of bioinsecticides in conjunction with parasitoids (25), life cycle parameters of *Sclerodermus* parasitoids (26), population dynamics of *Scymnus nubilus* (27) and life table parameters of *Liriomyza trifolii*. Additionally, SA has been employed to analyze pest thermotolerance (28) and is further extended to fiber optic service life testing as well as evaluating the field performance of sterile insect techniques in mosquito population control (29, 30).

This study employs Survival Analysis (SA) to analyze data from 16 insect species to evaluate the durability of insecticides. The primary objective is to determine the time required for the development of insecticide resistance, comparing the number of generations each species takes to evolve resistance and assessing the longevity of different MoA. By utilizing Kaplan-Meier estimation and log-rank tests, the study identifies significant variations in resistance development among primary cauliflower pests and their closely related species. Unlike previous research, which has broadly examined insecticide resistance across various arthropod species, this study specifically focuses on cauliflower pests and evaluates resistance dynamics at a regional scale. The findings offer a detailed understanding of the duration for which an insecticide remains effective against a particular pest species. This knowledge is critical for developing sustainable resistance management strategies, aiding policymakers and farmers in selecting more durable insecticides based on MoA and optimizing region-specific pest control programs by accounting for local insect reproductive rates.

Materials and Methods

Data description

The data for this study were obtained from the Arthropod Pesticide Resistance Database (APRD) and the Pesticide Properties Database (PPDB) (31, 32). To assess variations in insecticide longevity of efficacy among cauliflower pests and their closely related species, eight major cauliflower pests were selected based on the information available in Insecticide Resistance Action Committee (IRAC) database (33). To determine whether insecticide durability differs between key cauliflower pests and their phylogenetically related species, resistance data from the APRD were analyzed. The study focused on economically significant cauliflower pests and compared them with their closely related pest species worldwide to evaluate patterns of insecticide resistance development (34-36). All available records of pesticide resistance were compiled, including data

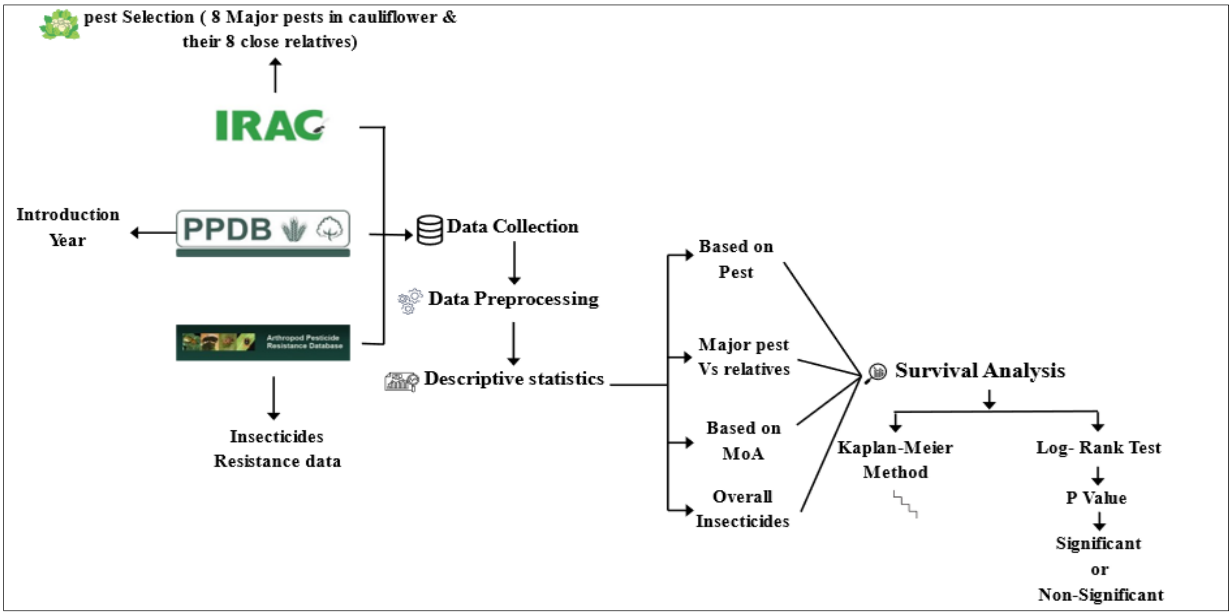


Fig. 1. Framework for survival analysis of insecticide resistance in cauliflower pests.

on the insecticide MoA for each pest species listed in the Supplementary file; Appendix I. Resistance data were systematically collected to assess susceptibility loss across various insecticides. The earliest documented instance of resistance for each pest-insecticide combination was identified and considered the initial resistance event. To determine the introduction date of each insecticide, launch dates were manually retrieved from the Pesticide Properties Database (PPDB). The time required for resistance development was then calculated by subtracting the insecticide's introduction date from the first recorded resistance event, providing insights into the durability of different insecticides across pest species. As pest species vary in their number of generations per year, adjustments were made to account for this variation by normalizing resistance data based on each species' average generation time. A total of 412 resistance cases were analyzed across 16 target insect species to evaluate patterns of insecticide resistance. Table 1 presents the list of species included in this analysis. Certain insecticides, such as those derived from *Bacillus* species, were excluded from the analysis because their commercial introduction dates are not documented in the PPDB as listed in the APRD. This absence of temporal data prevents the calculation of the interval between product launch and the first reported case of resistance, thereby compromising the accuracy of resistance development timelines.

This study assessed insecticide resistance on a global scale; however, variations in insect reproduction rates and damage potential exist across different geographic regions. For instance, *Plutella xylostella* can complete 14 to 16 generations per year under favorable climatic conditions like that in tropical regions, where higher temperatures accelerate metabolism and reproductive cycles. Conversely, under unfavorable climatic conditions, such as in temperate regions, the species produces only 3 to 4 generations per year, highlighting the influence of environmental factors on insect life cycle dynamics (37). Averaging resistance data across all regions may not yield meaningful insights due to regional variations in insect reproduction and environmental conditions. Therefore, the analysis was conducted on a regional basis to improve accuracy. This study may overestimate the time needed to develop resistance for two main reasons. First, resistance data are based on the publication date of reports, which inherently includes a time lag between the initial identification of resistance and the official documentation of the report. Second, the introduction date of an insecticide does not necessarily correspond to its first application against a specific pest, as its deployment may vary across regions and agricultural practices. Furthermore, this analysis is limited by the absence of resistance data for recently introduced insecticides, as resistance may not yet have developed or been officially documented. However, despite this lack of recorded cases, arthropod populations may already be undergoing the evolutionary process of resistance development, which could remain undetected due to delays in surveillance and reporting (38, 39).

Statistical analysis

Survival analysis encompasses various methodological approaches including parametric, non-parametric and semi-parametric models. In this study, the Kaplan-Meier estimator and log-rank test were employed to assess the time to resistance development in insect pests. These non-parametric methods were selected over the semi-parametric Cox proportional hazards model, as they do not rely on assumptions of proportional hazards and are well-suited for comparing survival distributions across groups. The Kaplan-Meier method effectively estimates median survival times, while the log-rank test facilitates the identification of statistically significant differences in resistance onset between species or regions. This approach is particularly appropriate when the primary objective is to describe and compare resistance timelines rather than evaluate the effect of multiple covariates. Fig. 1 provides a schematic representation of the overall methodological approach adopted in this study for analyzing insecticide resistance in major cauliflower pests using survival analysis. It outlines the

Table 1. List of species included in the analysis

Pests in cauliflower	Close relatives	Level of relationship
Plutella xylostella (Diamondback Moth) Cruciferous vegetables (Brassicaceae family)	*Bucculatrix thurberiella* (Cotton Leaf Perforator) Cotton (*Gossypium* spp.)	Superfamily (Yponomeutoidea)
Brevicoryne brassicae (Cabbage Aphid) Cruciferous vegetables (Brassicaceae family)	*Sitobion avenae* (English Grain Aphid) Cereal crops and grasses	Family (Aphididae)
Spodoptera litura (Tobacco Cutworm) Wide range of crops (polyphagous pest) - Tobacco, cotton, cabbage, etc	*Spodoptera frugiperda* (Fall Armyworm) Primarily maize but highly polyphagous	Genus (Spodoptera)
Trichoplusia ni (Cabbage Looper) Cruciferous crops and legumes	*Chrysodeixis includens* (Soybean Looper) Primarily legumes	Family (Noctuidae)
Spodoptera exigua (Beet Armyworm) Wide range of vegetables and crops - Sugar beet, onion, cotton, cabbage	*Spodoptera littoralis* (Egyptian Cotton Leafworm) Cotton and various vegetables	Genus (Spodoptera)
Psylliodes chrysocephala (Cabbage Stem Flea Beetle) Cruciferous vegetables (Brassicaceae family)	*Epitrix cucumeris* (Potato Flea Beetle) Hosts: Solanaceae family	Family (Chrysomelidae)
Frankliniella occidentalis (Western Flower Thrips) tomato, pepper, cabbage, broccoli, etc	*Thrips tabaci* Lindeman (Onion Thrips) Hosts: Onion, cabbage, tomato, cotton, etc	Family (Thripidae)
Helicoverpa zea (Corn Earworm) Cotton, tomato, maize, cabbage, cauliflower, etc	*Helicoverpa armigera* (Cotton Bollworm) Cotton, tomato, chickpea, pigeon pea, maize, etc	Genus (Helicoverpa)

sequential steps from pest and insecticide data collection to statistical evaluation using Kaplan-Meier estimates and log-rank tests.

Kaplan-Meier estimator

A key goal in time-to-event data analysis is to estimate and visualize the survival function using available data. One of the most commonly used methods for this purpose is the Kaplan-Meier (KM) estimator, which is a non-parametric technique for survival function estimation. Non-parametric methods are simple and do not rely on specific assumptions about the distribution of survival times. They are particularly useful for summarizing survival data and making basic comparisons, although they may be less effective in handling more complex scenarios (15, 40, 41).

Let $t_1 < t_2 < \ldots < t_k$ denote the observed event times and let $n = n_0$ represent the total sample size. The number of individuals experiencing an event at t_j (where $j = 1, 2, \ldots, k$) is denoted as d_j while m_j represents the number of individuals censored in the interval $[t_j, t_{j+1})$ The count of individuals at risk immediately before t_j is:

$$n_j = (m_j + d_j) + \ldots + (m_k + d_k) \qquad \text{Eqn. 1}$$

The Kaplan-Meier estimator, also known as the product-limit estimator, is expressed as:

$$\hat{S}(t) = \prod_{j:t_j \le t} \frac{n_j - d_j}{n_j} \qquad \text{Eqn. 2}$$

To estimate the standard errors, Greenwood's formula is applied, which approximates the variation as follows:

$$Var\left(\hat{S}(t)\right) = \hat{S}(t)^2 \sum_{j:t_j \le t} \frac{d_j}{n_j(n_j - d_j)} \qquad \text{Eqn. 3}$$

Log-rank test

Another key goal in survival data analysis is to compare survival times between two or more groups. A widely used statistical test for this purpose is the log-rank test, also known as the Mantel-Haenszel test. This test evaluates whether there is a significant difference in survival across groups and functions similarly to the chi-squared (X^2) test for association. Specifically, it tests the hypothesis that the survival functions $S_0(t), \ldots, S_p(t)$ are the same across different populations, using samples from each of *the* $p + 1$ groups. If h_j represents the hazard (the conditional probability of failure) at the time t_j the null hypothesis of the log-rank test assumes that h_j remains consistent across all $p + 1$ groups. The test statistic is derived by comparing the observed number of failures to the expected number and follows an asymptotic chi-squared (X^2) distribution under the null hypothesis. The degrees of freedom for the test are determined by p, which is the total number of groups minus one (16, 42).

Results and Discussion

Summary statistics

Based on pesticide introduction data from PPDB and field-level resistance onset data from APRD, Table 2 summarizes the mean number of generations required for key pest species to develop resistance to insecticides across tropical and temperate regions. *Plutella xylostella* is the predominant global pest of cauliflower and is characterized by a high

Table 2. Mean amount of time between an insecticide's introduction and each species' first documented occurrence of resistance

S.No.	Pests	Temperate region			Tropical region		
		Generation/ year	Mean generations until resistance	SD	Generation/ year	Mean generations until resistance	SD
1	*Bucculatrix thurberiella*	2	23	13.46	6	66	34.07
2	*Epitrix cucumeris*	2	27	6.43	3	41	9.64
3	*Spodoptera littoralis*	3	42	25.26	7	98	58.07
4	*Plutella xylostella*	4	52	27.18	14	160	69.37
5	*Trichoplusia ni*	2	27	13.91	12	126	45.65
6	*Spodoptera frugierda*	1	25	13.88	5	123	69.41
7	*Spodoptera exigua*	5	88	41.68	8	212	102.09
8	*Spodoptera litura*	3	64	23.71	12	220	80.46
9	*Chrysodeixis includens*	4	72	18.04	12	214	54.15
10	*Brevicoryne brassicae*	10	289	108.16	20	542	195.56
11	*Sitobion avenae*	19	553	94.63	17	495	84.68
12	*Psylliodes chrysocephala*	1	29	1.25	1	29	1.25
13	*Frankliniella occidentalis*	3	62	20.46	12	255	90.02
14	*Helicoverpa armigera*	3	55	21.49	8	147	57.31
15	*Helicoverpa zea*	3	60.66	9.46	5	115	33.98
16	*Thrips tabaci* Lindeman	3	71	23.34	10	246	76.85

*SD: Standard Deviation.

reproductive rate, as it produces approximately 14 to 20 generations per year in tropical regions and 4 to 6 generations in temperate zones. Based on this reproductive potential, resistance development was observed after an average of 160 generations in tropical regions and 52 generations in temperate regions. Similarly, *Trichoplusia ni* is a major pest of cauliflower that completes at least one generation per month in tropical regions and produces only 2 to 3 generations per year in temperate climates due to cooler summer temperatures. The analysis revealed that resistance in *Trichoplusia ni* emerged after approximately 126 generations in tropical regions and 27 generations in temperate regions. These findings suggest that although pests in tropical regions may experience more generations annually, resistance may develop over a longer cumulative time span, potentially due to fluctuating selection pressures or ecological variability that modulates resistance evolution. Likewise, *Sitobion avenae* produces 2 to 3 generations per year in temperate regions and 12 to 20 generations per year in tropical region. Considering pest reproduction rates per year, species like *Brevicoryne brassicae* and *Sitobion avenae* take longer to develop resistance in temperate regions. In tropical regions, *Sitobion* species took an average of over 495 generations to develop resistance. Similarly, *Brevicoryne brassicae* required more than 289 generations to develop resistance in both regions. The Standard Deviation (SD) column indicates the variation or spread of the number of generations until resistance developed for each species. A lower SD value shows that the time (in generations) until resistance developed was relatively consistent across different cases. For example, *Bucculatrix thurberiella*, *Spodoptera frugiperda* and *Trichoplusia ni* showed relatively uniform resistance development patterns. The average number of generations required for resistance to emerge was 23, 25 and 27 respectively, with SD of 13.46, 13.88 and 13.91. These low SD values indicate minimal variation in resistance onset across different insecticides, suggesting that resistance in these species tends to arise within a consistent generational range regardless of the chemical involved. In contrast, *Brevicoryne brassicae* exhibited considerable variability. Resistance developed after an average of 542 generations in tropical regions and 289 generations in temperate zones with high SDs of 195.56 and 108.16 respectively. This suggests that the timeline for resistance development in this species is highly variable and may be influenced by differences in insecticide exposure, genetic factors or localized pest management strategies. Interestingly, *Psylliodes chrysocephala* showed identical mean and SD values in both tropical and temperate regions, indicating stable resistance dynamics across climatic zones. This consistency implies that environmental factors such as temperature or regional application practices may have limited influence on resistance evolution in this species (43).

Based on insect species

Significant variation was observed among the 16 pest species in terms of insecticide longevity, with statistical significance recorded at less than 1 % (log-rank test, $p < 0.0001$). Fig. 2 and 3 present the results using Kaplan-Meier survival curves across all regions, showing the proportion of insecticides that remained effective over time until documented resistance emerged. In these curves, horizontal flat lines represent periods during which no resistance events were reported, while each downward step corresponds to a resistance event, indicating the point at which a pest population exhibited resistance to a specific insecticide. This analytical approach effectively visualizes the temporal dynamics of resistance development across multiple pest species. The survival patterns demonstrate that resistance often emerged within a relatively short number of generations. Among the species analyzed, *Plutella xylostella*, *Trichoplusia ni* and *Spodoptera* spp. displayed resistance to a greater number of insecticides, suggesting a higher evolutionary potential for resistance and broader adaptive capacity compared to other pest species.

Based on major pests and their close relatives

Fig. 4 and 5 illustrate that major cauliflower pest species differ from their relatives in the rate at which resistance develops across tropical and temperate regions. Some of these closely

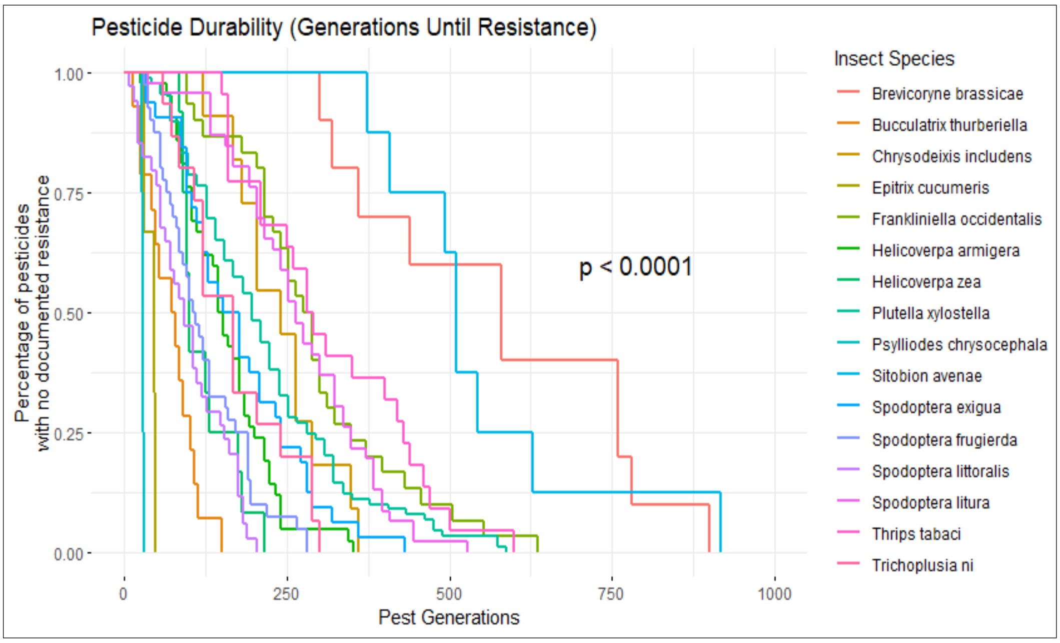


Fig. 2. Survival curves for each of the 16 species in the tropical region.

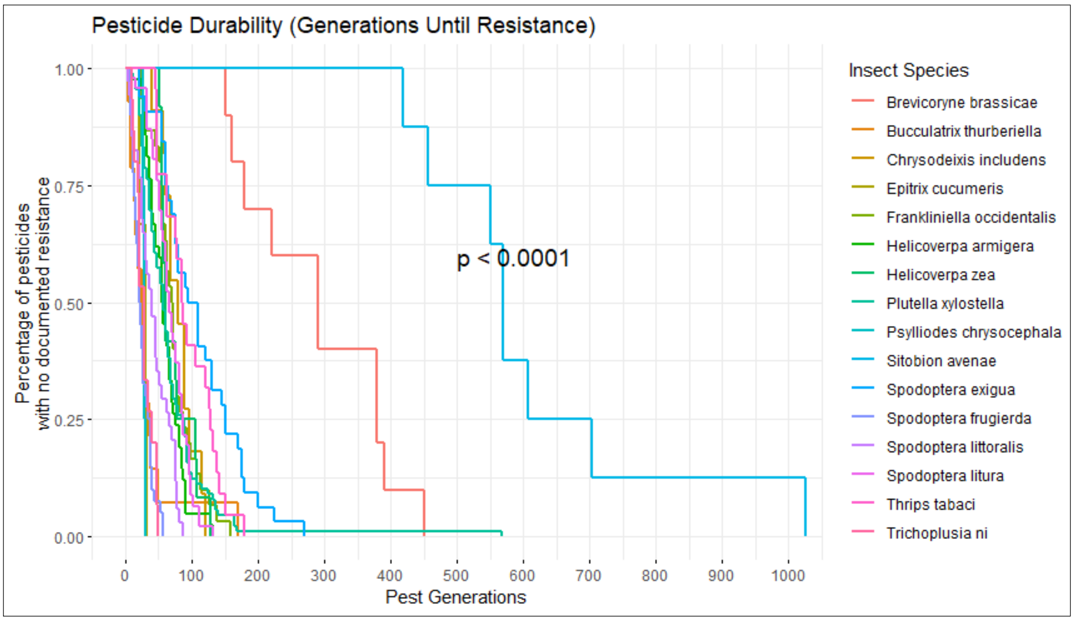


Fig. 3. Survival curves for each of the 16 species in the temperate region.

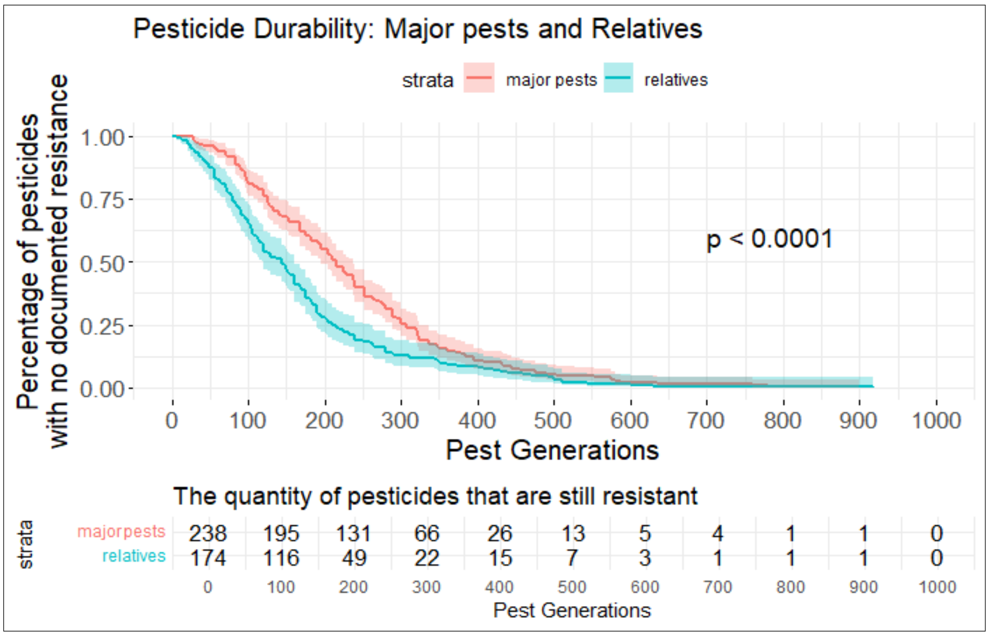


Fig. 4. Comparison of pesticide survival curves in tropical region against the majority of resistant pests and their close relatives.

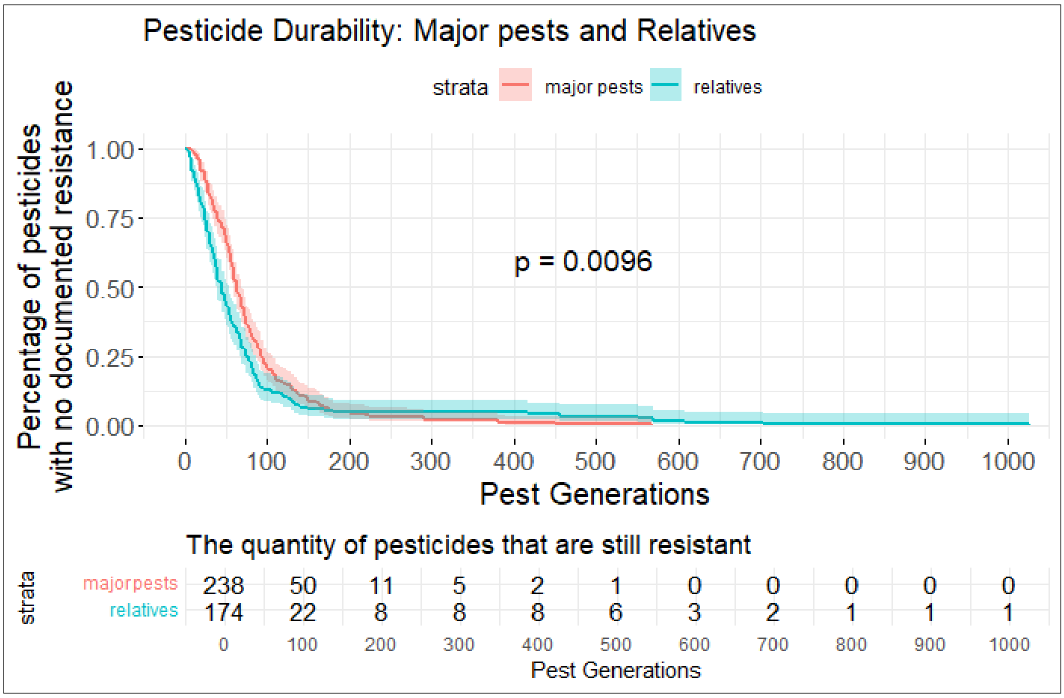


Fig. 5. comparison of pesticide survival curves in temperate region against the majority of resistant pests and their close relatives.

related species, which are also significant pests in other crops, have been documented to develop resistance at a faster rate than major cauliflower pests. This accelerated evolution of resistance may be attributed to genetic similarities, as closely related species have been shown to share physiological and metabolic characteristics that can influence their response to insecticides. These shared traits may include enhanced detoxification mechanisms, mutations at insecticide target sites, or behavioural adaptations that improve survival following insecticide exposure. As a result, pest species closely related to those with known resistance may evolve resistance more rapidly when exposed to similar insecticides, creating substantial challenges for pest management strategies and resistance mitigation efforts.

Fig. 4 demonstrates that by the 100th generation, 195 insecticide-species pairings remained without reported resistance out of a total of 238 pairings for the most resistant species. In comparison, 116 out of 174 pairings exhibited no resistance among their closely related species. The variation in resistance development among species is considerable. Certain species, such as *Bucculatrix thurberiella*, *Spodoptera littoralis*, *Helicoverpa armigera*, *Psylliodes chrysocephala* and *Plutella xylostella*, exhibited rapid resistance evolution, with resistance to specific insecticides emerging within two years of exposure. Conversely, other species, including Spodoptera litura and Brevicoryne brassicae, required a greater number of generations to develop resistance to particular insecticides, indicating species-specific differences in resistance evolution rates (44, 45).

In temperate regions, insect pests tend to develop resistance earlier within their generations, with a statistically significant difference observed at a *p*-value of 0.0096. Despite producing fewer generations annually due to unfavorable climatic conditions that limit insect reproduction. By the 100th generation, the analysis reveals that 50 insecticide-species pairings among pest species remained without documented resistance out of a total of 238 pairings, whereas only 22 out of 174 pairings exhibited no resistance among their closely related species. The findings emphasized that managing resistant pest species is of greater importance than managing their closely related species, as these major pests undergo more generations per year, leading to persistent infestations and causing substantial economic losses in agricultural production (46). In tropical regions, pest species exhibit a higher number of generations per year compared to those in temperate regions, where unfavorable climatic conditions restrict their reproductive cycles (47, 48). Consequently, in tropical areas, resistant pest species persist in the field throughout the year, posing a continuous threat at all stages of cauliflower growth. In contrast, in temperate regions, the presence of resistant species is limited to periods of favorable environmental conditions. Although resistant species and their closely related counterparts share certain physiological and ecological characteristics, the later generally cause less economic damage due to their comparatively lower reproductive rates and limited seasonal activity.

Based on Mode of Actions

The duration of insecticidal effectiveness significantly varies depending on its MoA, as supported by statistical evidence. In tropical regions (Fig. 6), this variation was highly significant (*p* = 0.001) and indicated marked differences in resistance development timelines among MoA groups. Similarly, a significant effect was observed in temperate regions (Fig. 7) with a p-value of 0.0048, though the magnitude of variation was comparatively lower than in tropical climates. In both cases, *p*-values below 0.05 confirm that these differences are statistically meaningful and not due to random chance. Each survival curve in the figures represents a distinct MoA group. Steeper declines in these curves reflect faster resistance emergence, highlighting the need for cautious use and rotation of such insecticides. Conversely, MoA groups with more gradual declines indicate longer-lasting effectiveness and may be more suitable for integration into long-term resistance management and sustainable pest control strategies. Most insecticides

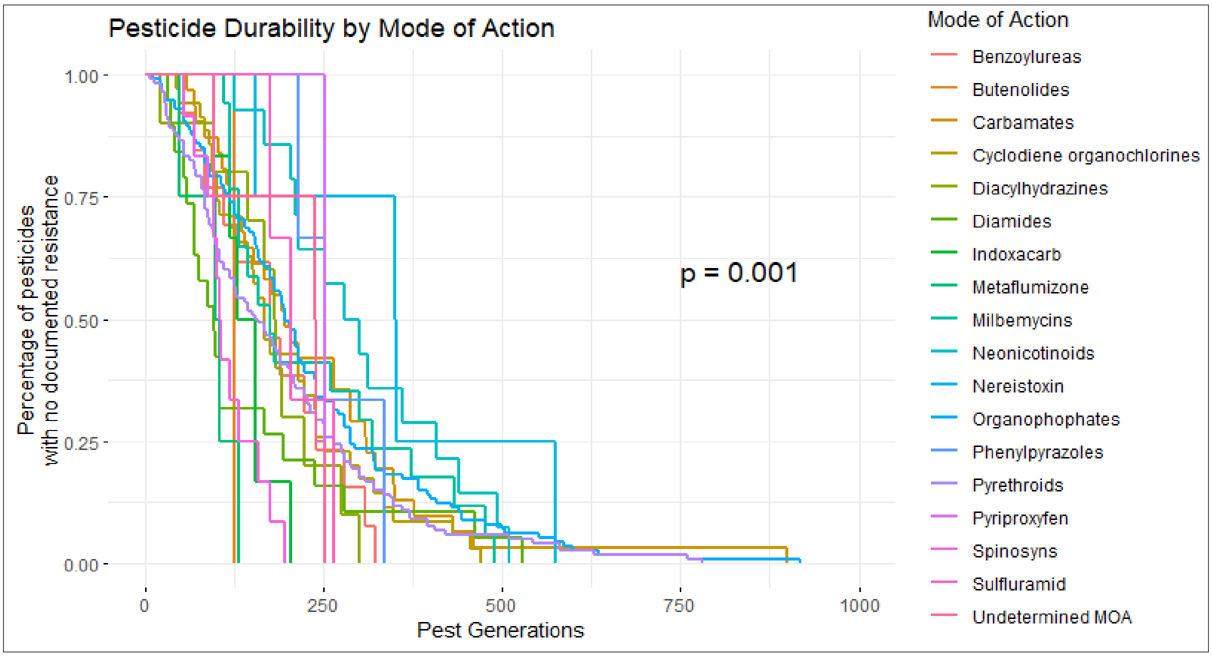


Fig. 6. Pesticide durability by Mode of Action (MoA) in tropical region is depicted by survival curves.

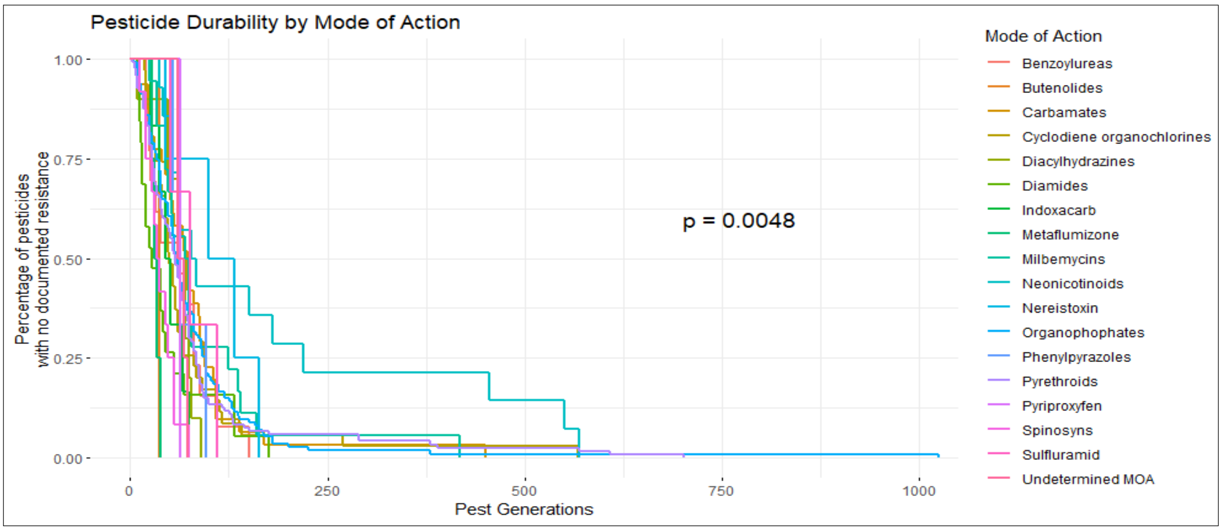


Fig. 7. Pesticide durability by Mode of Action (MoA) in temperate region is depicted by survival curves.

belong to specific MoAs, including Carbamates, Organophosphates and Pyrethroids. Carbamates function as acetylcholinesterase (AChE) inhibitors, blocking the enzyme acetylcholinesterase, which is essential for normal nerve function. Similarly, Organophosphates act as AChE inhibitors, disrupting neural signaling by preventing the breakdown of acetylcholine, leading to nerve overstimulation and paralysis. Pyrethroids, on the other hand, target voltage-gated sodium channels in the insect nervous system, causing prolonged nerve excitation and eventual insect mortality. These insecticides, despite their effectiveness, are prone to resistance development due to their specific target sites. In contrast, insecticides belonging to MoAs such as Diacylhydrazines, Phenylpyrazoles, Milbemycins, Nereistoxin, Diamides, Spinosyns, Sulfluramid and Phenylpyrazoles exhibit more gradual decline curves. This trend suggests that these insecticides retain their effectiveness for a longer duration, likely due to slower resistance evolution. The prolonged efficacy of these MoAs may be attributed to their unique biochemical targets, reduced selection pressure, or lower frequency of application compared to rapidly declining MoAs.

Based on overall insecticides

Fig. 8 illustrates that in tropical regions the median number of generations between the initial registration of an insecticide and the first reported resistance case was 178. In contrast, temperate regions (Fig. 9) exhibited a markedly lower median of 56.5 generations. This substantial difference underscores the role of climatic conditions in shaping pest population dynamics and resistance evolution. Tropical climates generally support higher reproductive rates due to consistent warmth and extended growing seasons, allowing pest species to complete a greater number of generations annually. Consequently, pests in these regions are exposed more frequently to insecticides, which can intensify selection pressure and facilitate the rapid development of resistance. In temperate zones, cooler temperatures limit the number of pest generations per year, potentially slowing resistance onset despite the use of similar insecticides. This comparison highlights the need for region-specific resistance

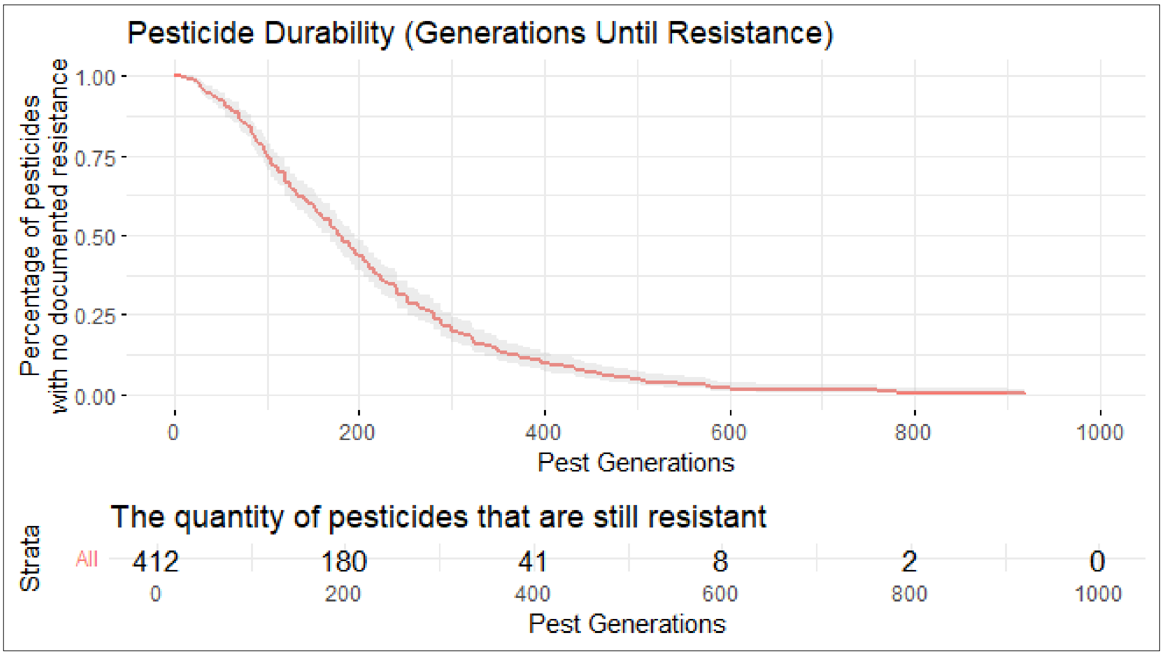


Fig. 8. The overall survival curve for all insecticides against these 16 species in tropical region.

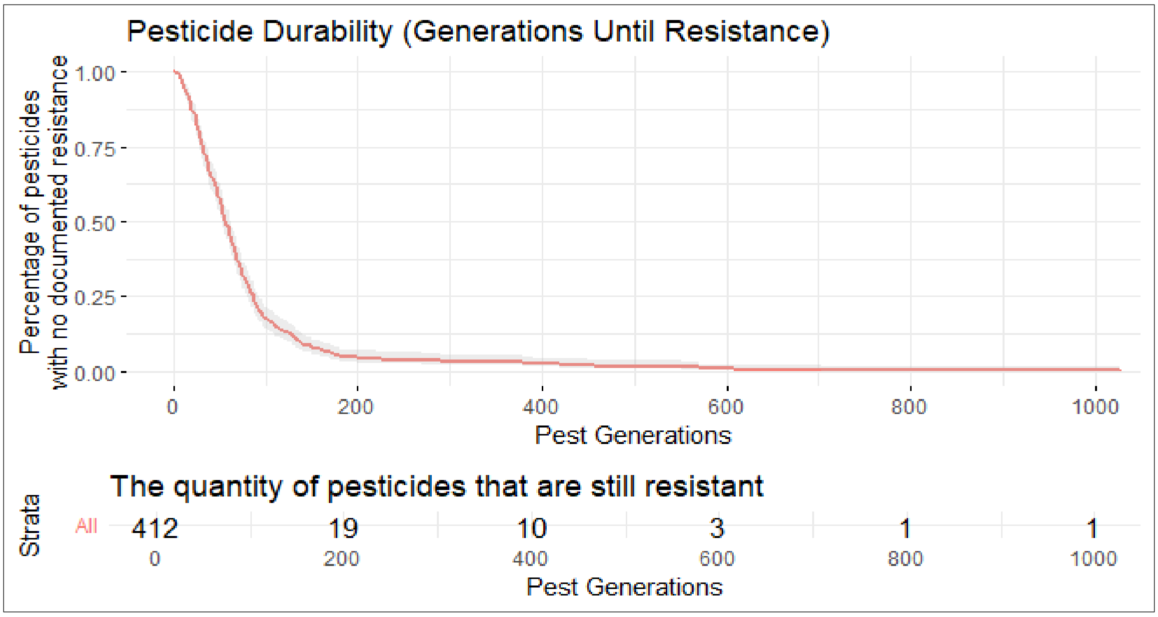
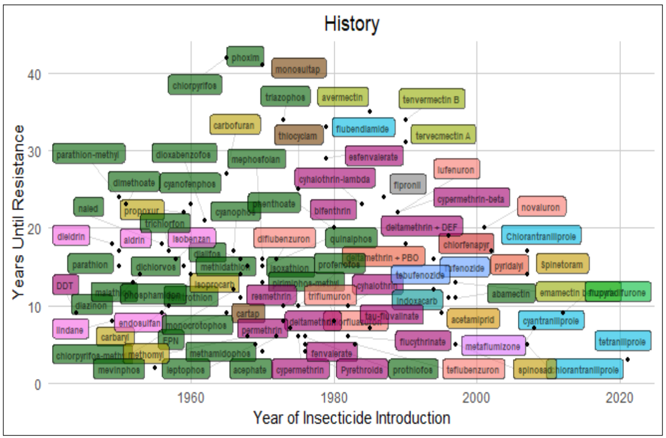


Fig. 9. The overall survival curve for all insecticides against these 16 species in temperate region.

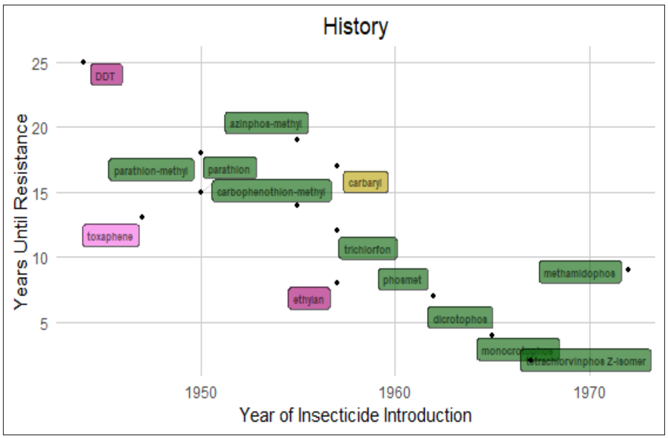
Table 3. Median generations until resistance evaluation across all regions based on Mode of Action.

S.No.	Mode of Action	Tropical region	Temperate region
1	Benzoylureas	176	64
2	Butenolides	126	36
3	Carbamates	196	72
4	Cyclodiene organochlorines	168	50
5	Diacylhydrazines	183	66.5
6	Diamides	96	28
7	Indoxacarb	142	47.5
8	Metaflumizone	101	31.5
9	Milbemycins	175	72.5
10	Neonicotinoids	290	81
11	Nereistoxin	351	116
12	Organophophates	196	60
13	Phenylpyrazoles	252	63
14	Pyrethroids	157	57
15	Pyriproxyfen	252	63
16	Spinosyns	106.5	34.5
17	Sulfluramid	204	76
18	Undetermined MOA	239	64

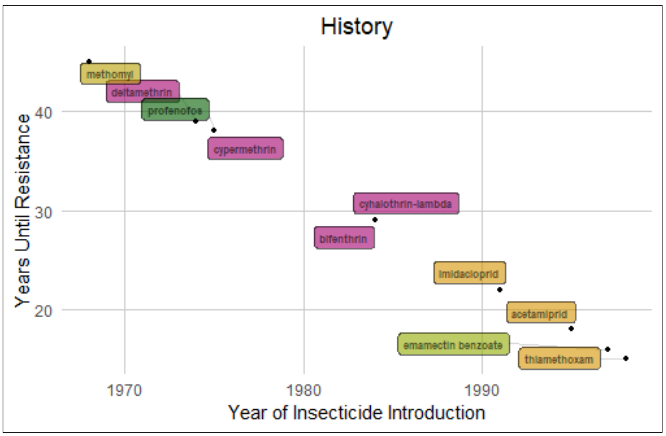
management strategies, considering ecological factors that influence the tempo of resistance evolution. This analysis categorized pesticides based on their MoA and evaluated the time required for resistance to develop after their introduction. Table 3 presents the median number of generations required for resistance to emerge for each MoA. Insecticides such as Diamides, Spinosyns and Milbemycins (which share similarities with Avermectins) have had relatively lower exposure compared to other pesticide groups. This limited exposure may contribute to their prolonged effectiveness in the field. The findings indicate that the durability of these insecticides, in terms of field-evolved resistance, varies across different regions, emphasizing the role of environmental and ecological factors in resistance development. For example, in the tropical region, the estimated longevity for Diamondback moth control is approximately 7 years for Diamides, 8.5 years for Spinosyns and 12.9 years for Milbemycins. In temperate regions, the estimated longevity of insecticides is 7 years for Diamides, 9.75 years for Spinosyns and 18.75 years for Milbemycins. These estimates


History
Years Until Resistance
0
10
20
30
40
Year of Insecticide Introduction
1960
1980
2000
2020
phoxim
monosultap
chlorpyrifos
triazophos
avermectin
tenvermectin B
carbofuran
thiocyclam
flubendiamide
tervecmectin A
parathion-methyl
dioxabenzofos
mephosfolan
esfenvalerate
lufenuron
dimethoate
cyanofenphos
cyhalothrin-lambda
fipronil
cypermethrin-beta
naled
propoxur
cyanophos
phenthoate
bifenthrin
novaluron
trichlorfon
deltamethrin + DEF
dieldrin
aldrin
isobenzan
diflubenzuron
quinalphos
chlorfenapyr
Chlorantraniliprole
dialifos
deltamethrin + PBO
parathion
dichlorvos
methidathion
isoxathion
profenofos
tebufenozide
pyridalyl
spinetoram
DDT
isoprocarb
pirimiphos-methyl
cyhalothrin
malathion
phosphamidon
fenitrothion
resmethrin
triflumuron
indoxacarb
abamectin
emamectin benzoate
flupyradifurone
diazinon
cartap
tau-fluvalinate
acetamiprid
cyantraniliprole
lindane
endosulfan
monocrotophos
deltamethrin
chlorfluazuron
permethrin
carbaryl
EPN
flucythrinate
metaflumizone
tetraniliprole
chlorpyrifos-methyl
methomyl
methamidophos
fenvalerate
mevinphos
leptophos
acephate
cypermethrin
Pyrethroids
prothiofos
teflubenzuron
spinosad
chlorantraniliprole

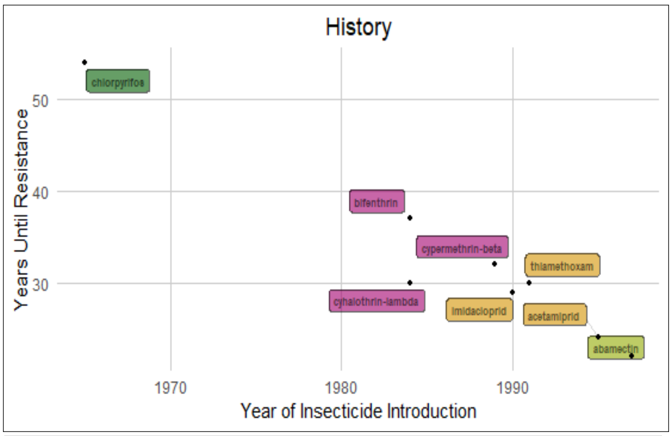
a


History
Years Until Resistance
5
10
15
20
25
Year of Insecticide Introduction
1950
1960
1970
DDT
azinphos-methyl
parathion-methyl
parathion
carbaryl
carbophenothion-methyl
toxaphene
trichlorfon
methamidophos
phosmet
ethylan
dicrotophos
monocrotophos
tetrachlorvinphos Z-isomer

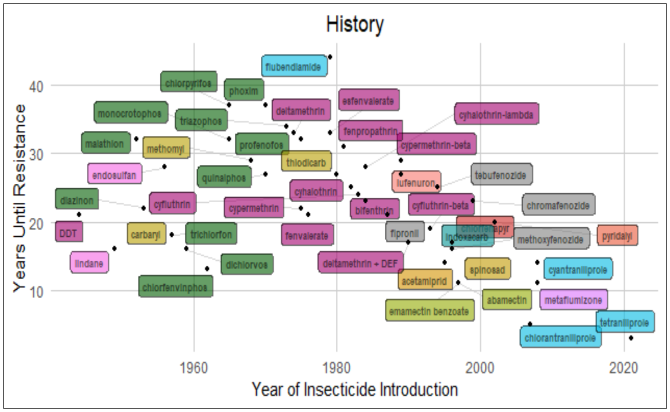
b


History
Years Until Resistance
20
30
40
Year of Insecticide Introduction
1970
1980
1990
methomyl
deltamethrin
profenofos
cypermethrin
cyhalothrin-lambda
bifenthrin
imidacloprid
acetamiprid
emamectin benzoate
thiamethoxam

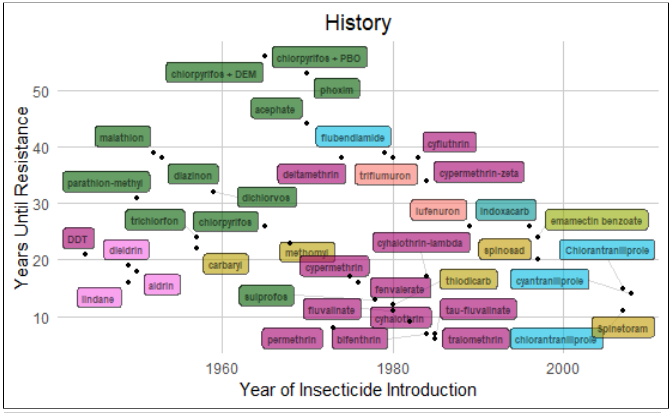
c


History
Years Until Resistance
30
40
50
Year of Insecticide Introduction
1970
1980
1990
chlorpyrifos
bifenthrin
cypermethrin-beta
thiamethoxam
cyhalothrin-lambda
imidacloprid
acetamiprid
abamectin

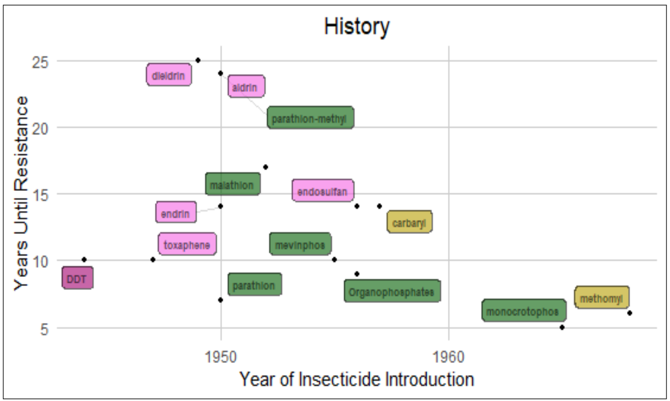
d


History
Years Until Resistance
10
20
30
40
Year of Insecticide Introduction
1960
1980
2000
2020
flubendiamide
chlorpyrifos
phoxim
esfenvalerate
monocrotophos
triazophos
deltamethrin
cyhalothrin-lambda
fenpropathrin
malathion
methomyl
profenofos
cypermethrin-beta
thiodicarb
endosulfan
quinalphos
tebufenozide
lufenuron
cyhalothrin
diazinon
cyfluthrin
cypermethrin
cyfluthrin-beta
chromafenozide
bifenthrin
DDT
carbaryl
trichlorfon
fenvalerate
chlorfenapyr
fipronil
indoxacarb
methoxyfenozide
pyridalyl
lindane
dichlorvos
deltamethrin + DEF
spinosad
cyantraniliprole
chlorfenvinphos
acetamiprid
abamectin
metaflumizone
emamectin benzoate
tetraniliprole
chlorantraniliprole

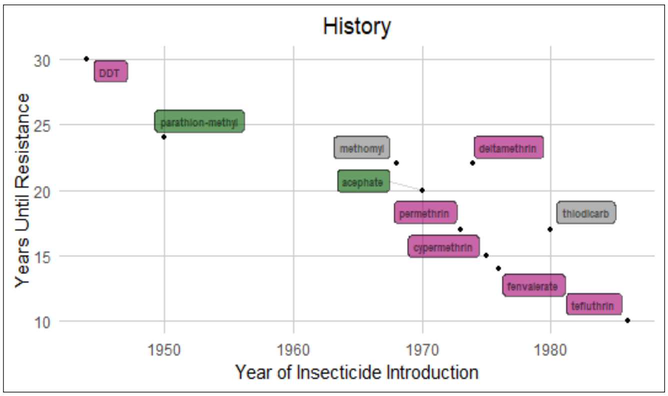
e


History
Years Until Resistance
10
20
30
40
50
Year of Insecticide Introduction
1960
1980
2000
chlorpyrifos + PBO
chlorpyrifos + DEM
phoxim
acephate
malathion
flubendiamide
cyfluthrin
parathion-methyl
diazinon
deltamethrin
triflumuron
cypermethrin-zeta
dichlorvos
lufenuron
indoxacarb
emamectin benzoate
trichlorfon
chlorpyrifos
DDT
dieldrin
methomyl
cyhalothrin-lambda
spinosad
Chlorantraniliprole
carbaryl
cypermethrin
aldrin
fenvalerate
thiodicarb
cyantraniliprole
lindane
sulprofos
fluvalinate
cyhalothrin
tau-fluvalinate
permethrin
bifenthrin
tralomethrin
chlorantraniliprole
spinetoram

f


History
Years Until Resistance
5
10
15
20
25
Year of Insecticide Introduction
1950
1960
dieldrin
aldrin
parathion-methyl
malathion
endosulfan
endrin
carbaryl
toxaphene
mevinphos
DDT
parathion
Organophosphates
monocrotophos
methomyl

g


History
Years Until Resistance
10
15
20
25
30
Year of Insecticide Introduction
1950
1960
1970
1980
DDT
parathion-methyl
methomyl
deltamethrin
acephate
thiodicarb
permethrin
cypermethrin
fenvalerate
tefluthrin

h

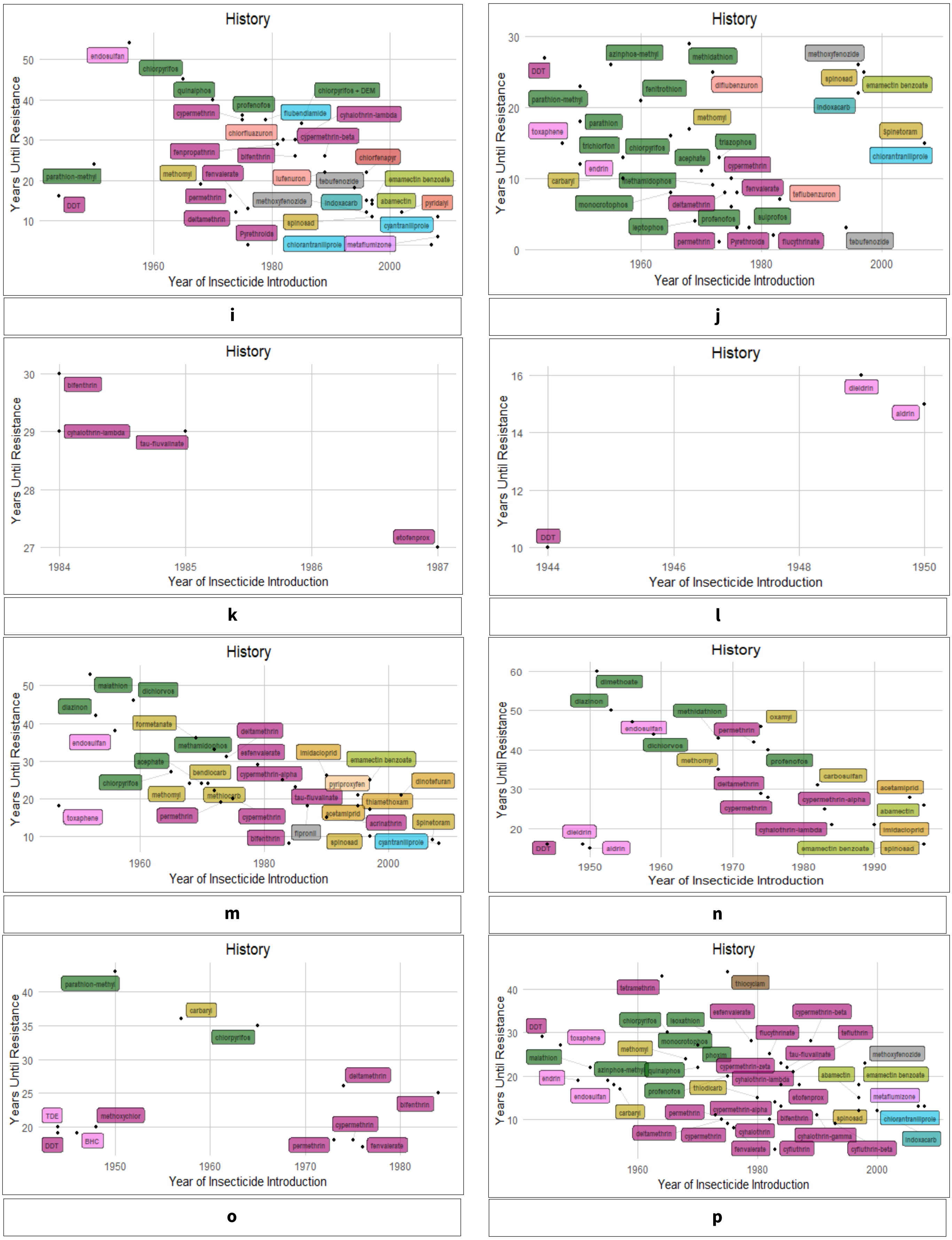


Fig. 10. History of insecticide introduction and subsequent emergence of resistance in different pest species. (a) History of insecticide resistance in *Plutella xylostella*, (b) History of insecticide resistance in *Bucculatrix thurberiella*, (c) History of insecticide resistance in *Brevicoryne brassicae*, (d) History of insecticide resistance in *Sitobion avenae*, (e) History of insecticide resistance in *Spodoptera litura*, (f) History of insecticide resistance in *Spodoptera frugierda*, (g) History of insecticide resistance in *Trichoplusia ni*, (h) History of insecticide resistance in *Chrysodeixis includens*, (i) History of insecticide resistance in *Spodoptera exigua*, (j) History of insecticide resistance in *Spodoptera littoralis*, (k) History of insecticide resistance in *Psylliodes chrysocephala*, (l) History of insecticide resistance in *Epitrix cucumeris*, (m) History of insecticide resistance in *Frankliniella occidentalis*, (n) History of insecticide resistance in *Thrips tabaci*, (o) History of insecticide resistance in *Helicoverpa zea* and (p) History of insecticide resistance in *Helicoverpa armigera.*

apply when insecticides with the same MoA are used in an alternating manner to maintain their effectiveness over time.

Fig. 10(a-p), graphically illustrates the timeline of pesticide introduction and the subsequent emergence of resistance for each pest species analyzed (13). These figures provide a concise summary of the resistance evolution patterns observed in individual pest species. In this plot, each pesticide is labelled by name and color-coded according to its MoA, allowing for a clear visual representation of resistance development across different insecticide classes. The graphical representation indicates that early-introduced insecticides, such as DDT, toxaphene and lindane, remained effective for over 100 generations before resistance was reported in tropical regions. This suggests that, while initial resistance development was relatively slow, subsequent advancements in pesticide formulations and increased exposure may have accelerated resistance evolution in more recently introduced compounds. In temperate regions, certain insecticides required more than a decade for resistance to emerge, indicating that pests initially took a relatively long time to evolve resistance. However, more recently introduced insecticides such as tetraniliprole, chlorantraniliprole, cyantraniliprole, metaflumizone and flupyradifurone developed after the 21st century exhibited a much faster resistance evolution. Notably, tetraniliprole showed resistance within just three years of its introduction. This trend suggests that newer insecticides may be subject to more rapid resistance development, likely driven by increased selection pressure, pre-existing resistance mechanisms, or enhanced genetic adaptability in pest populations.

The tropical region graph indicates that in *Plutella xylostella*, resistance to the insecticides-chlorpyrifos, phoxim and avermectin, which were introduced early, took over 500 generations to develop, while in temperate regions, the same chemicals took less than 170 generations for resistance to emerge. This suggests that in earlier periods, pests took a relatively long time to evolve resistance to these insecticides. In contrast, tetraniliprole, introduced in 2021, showed much faster resistance development within 42 generations in tropical regions and 12 generations in temperate regions indicating that newer insecticides may face quicker resistance development, possibly due to stronger selection pressure or genetic adaptation. Similarly, DDT, introduced as an agricultural insecticide in 1944, exhibited considerable variation in the time taken for resistance to develop among species, ranging from 10 generations for *Trichoplusia ni* to 120 generations for *Chrysodeixis includens* in temperate regions and up to 360 generations for *Chrysodeixis includens* in tropical region.

Conclusion

The study identified significant differences in resistance development across individual pest species, their closely related counterparts and insecticide groups sharing the same MoA. Pests with frequent outbreaks such as *Plutella xylostella* are exposed to more insecticides, accelerating resistance, whereas others like *Sitobion avenae*, *Chrysodeixis includens*, *Brevicoryne brassicae*, *Psylliodes chrysocephala* and *Epitrix cucumeris* evolve resistance more slowly due to limited exposure. The analysis, focused specifically on cauliflower pests, avoids confounding factors seen when mixing household and agricultural pests or species with divergent resistance profiles. Results suggest that pest phylogenetic relatedness influences resistance emergence through shared insecticide exposure, genetic traits and metabolic capacities. If resistance emerges in closely related species, there is a high possibility that cauliflower pests will also develop resistance due to shared genetic and physiological traits. Insecticide effectiveness further depends on MoA, with median values per MoA group providing predictive insight into expected insecticide longevity. These findings support the need for crop-specific resistance monitoring and integration of phylogenetic risk factors into insecticide rotation. Incorporating such insights into Integrated Pest Management (IPM) programs and regulatory frameworks can enhance long-term sustainability of pest control strategies. Future research can integrate genomic data with survival analysis to uncover genetic factors influencing resistance timelines in cauliflower pests. Expanding the model to include environmental, agronomic and IPM variables will enhance predictive accuracy and inform region-specific resistance management strategies. Additionally, developing real-time, crop -specific resistance monitoring tools could support evidence-based policy and farmer decision-making.

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Authors' contributions

M.N and BK outlined the research idea; MK involved in collection of information in the regarding field; MN and SV carried out analysis and brought out the interpretation; MN prepared the manuscript draft; CSS, MV and GB supervised the manuscript preparation and provided feedback and approval.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no competing interests, financial or non-financial. This work received no specific grant from any funding agency.

Ethical issues: None

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