



## Resistance to Lambda-Cyhalothrin and Deltamethrin with Associated Fitness Costs in a Tomato-Derived Population of *Helicoverpa armigera* (Lepidoptera: Noctuidae)

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### ABSTRACT

A field population of *Helicoverpa armigera* collected from tomato at Pirsabak was compared with a susceptible laboratory strain to characterise pyrethroid resistance, cross-resistance, and associated life-history costs. Leaf-dip bioassays produced resistance ratios of 142.6 for lambda-cyhalothrin and 89.4 for deltamethrin, whereas the chlorantraniliprole ratio was 1.8. The resistant population developed more slowly, had lower survival and pupal weight, and produced fewer viable eggs. Fecundity declined by 26.5%, and egg viability declined by 21.4 percentage points, equivalent to a 22.6% relative reduction. The results support suspension of routine pyrethroid use where resistance is confirmed and rotation across effective modes of action. The concentration-mortality curves are reconstructed from supplied LC<sub>50</sub> and slope parameters and are illustrative; raw dose-level mortality records are required for publication-grade verification.

### 1. Introduction

Tomato production exposes *Helicoverpa armigera* populations to a mosaic of insecticide treatments, as adults are highly mobile and move among vegetable, cotton, and other host crops across agricultural landscapes. Consequently, a resistance phenotype detected in tomato may reflect selection accumulated over a broader production region rather than exposure within a single field. This mobility makes local bioassays essential; regional recommendations based solely on historic efficacy can fail when immigrants carry resistance alleles or when local populations have experienced repeated applications of the same mode of action. Monitoring should therefore be interpreted as a time-specific estimate of susceptibility, not as a permanent property of the species (Fitt, 1989; Walsh et al., 2018).

Cross-resistance is operationally critical because nominal product rotation may provide little evolutionary diversification. Lambda-cyhalothrin and deltamethrin are both pyrethroids that act on voltage-gated sodium channels; resistance arising from altered target-site sensitivity or broad-spectrum detoxification can therefore reduce susceptibility to both compounds.

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Metabolic resistance is particularly challenging because cytochrome P450 monooxygenases and associated enzyme systems may process multiple active ingredients, while reduced cuticular penetration can delay toxicant delivery and further shift concentration–mortality responses (Ahmad et al., 2008; Li et al., 2007; Scott, 1999).

Fitness-cost measurements add a second dimension to toxicological surveillance. A resistance ratio describes the concentration shift required to achieve a defined mortality response, whereas development, survival, and reproduction indicate how the resistant phenotype performs when insecticide selection is absent. Detectable costs can favour susceptible alleles during periods without pyrethroid exposure, but this outcome is not guaranteed. Dominance, linkage, host plant, colony history, and compensatory evolution can all alter both the magnitude and stability of any fitness cost (Roush & McKenzie, 1987; Gassmann et al., 2009). The present comparison was therefore interpreted as evidence of associated life-history trade-offs rather than proof of a specific resistance mechanism.

*Helicoverpa armigera* is a highly mobile, polyphagous moth whose ecology enables rapid colonization of diverse crops and repeated exposure to insecticides across landscapes (Fitt, 1989). Intensive selection in cotton, tomato, and other hosts has produced geographically variable but often severe resistance problems (Kranthi et al., 2001). Pyrethroids act primarily on voltage-gated sodium channels, but field resistance can involve both target-site insensitivity and enhanced detoxification (French-Constant, 2013). Cytochrome P450-mediated metabolism is especially important because broad substrate specificity can generate cross-resistance among related or even chemically distinct compounds (Scott, 1999). Cross-resistance reduces the effective number of control options and may produce unexpected failures when products are rotated only by trade name rather than mode of action (Sparks & Nauen, 2015). Comparative studies among heliothine pests show that selection history, migration, and standing genetic variation strongly influence the route and speed of resistance evolution (Walsh et al., 2018). Resistance alleles can also impose fitness costs when the selecting insecticide is absent, affecting development, survival, mating, or reproduction (Roush & McKenzie, 1987). Such costs may slow resistance evolution or permit susceptibility to recover, but compensatory evolution and genetic background can reduce that opportunity (Gassmann et al., 2009). Operational resistance management therefore requires both toxicological monitoring and life-history interpretation (Denholm & Rowland, 1992). The present study evaluates lambda-cyhalothrin resistance, cross-resistance to deltamethrin and chlorantraniliprole, and potential fitness costs in a tomato-derived population from Pirsabak (Heckel, 2012). The specific objectives were to estimate LC<sub>50</sub> values and resistance ratios for three insecticides; compare probit slopes and heterogeneity between susceptible and field populations; measure larval and pupal development, survival, pupal weight, fecundity, and egg viability; distinguish percentage-point from relative percentage changes in egg viability; and translate the findings into practical insecticide resistance-management recommendations.

## 2. Materials and Methods

Larvae of *Helicoverpa armigera* were collected from tomato fruit and foliage at CCRI Pirsabak and surrounding farms during the 2024–2025 season, with collection date, crop stage, prior spray history, and number of founding individuals recorded to ensure colony representativeness. A susceptible laboratory strain with documented origin and maintained without insecticide exposure served as the reference comparator. Both strains were reared under identical temperature, humidity, photoperiod, host material, and larval density conditions before testing to ensure that environmental differences were not mistaken for genetic resistance. For bioassays, tomato leaves were immersed in insecticide solutions for 10 seconds, air-dried for 2 hours, and offered to third-instar larvae; ten larvae were used per concentration with four replicates, mortality was recorded at 48 hours, and control mortality was corrected using Abbott's formula when appropriate. The concentration series for lambda-cyhalothrin and deltamethrin ranged from 0.1 to 1000 ppm, while chlorantraniliprole concentrations ranged from 0.01 to 100 ppm, with each series designed to bracket approximately 5–95% mortality in both strains. Untreated and solvent controls were included in every assay run, and larvae were assigned randomly to concentrations with scoring conducted blind where practical to minimize observer bias. Probit analysis was fitted to the number dead and number exposed at each concentration, with the final report including slope, intercept, standard error, goodness-of-fit, heterogeneity factor, LC<sub>50</sub>, and confidence limits for each strain–insecticide combination. Resistance ratio was calculated as field-population LC<sub>50</sub> divided by susceptible-strain LC<sub>50</sub>, with confidence intervals obtained by methods that propagate uncertainty from both estimates. For fitness assessment, one hundred neonates per strain were reared individually on untreated tomato foliage to prevent cannibalism and allow development time and survival to be linked to each insect; ten adult pairs per strain were maintained to estimate fecundity and egg viability, with pairs formed from unrelated families where possible. Larval and pupal development duration, survival to pupation, pupal weight, fecundity, and egg viability were recorded for both strains. Statistical analyses employed linear models for continuous traits such as development time and pupal mass, binomial models for survival and hatch proportions, and count models for fecundity after checking for overdispersion; strain was treated as the main fixed effect, with family or cohort included as random effects where the design supported them. Effect sizes and confidence intervals were reported alongside P values to indicate biological magnitude, and all analyses were performed with the understanding that the original replicate-level observations were unavailable, so the current estimates and inferential results are retained from the supplied manuscript.

without recalculation. Resistance categories are descriptive and do not replace field-efficacy confirmation; the study does not establish mechanistic resistance pathways, and the results should be interpreted as time-specific estimates of susceptibility rather than permanent properties of the population.

### 3. Results

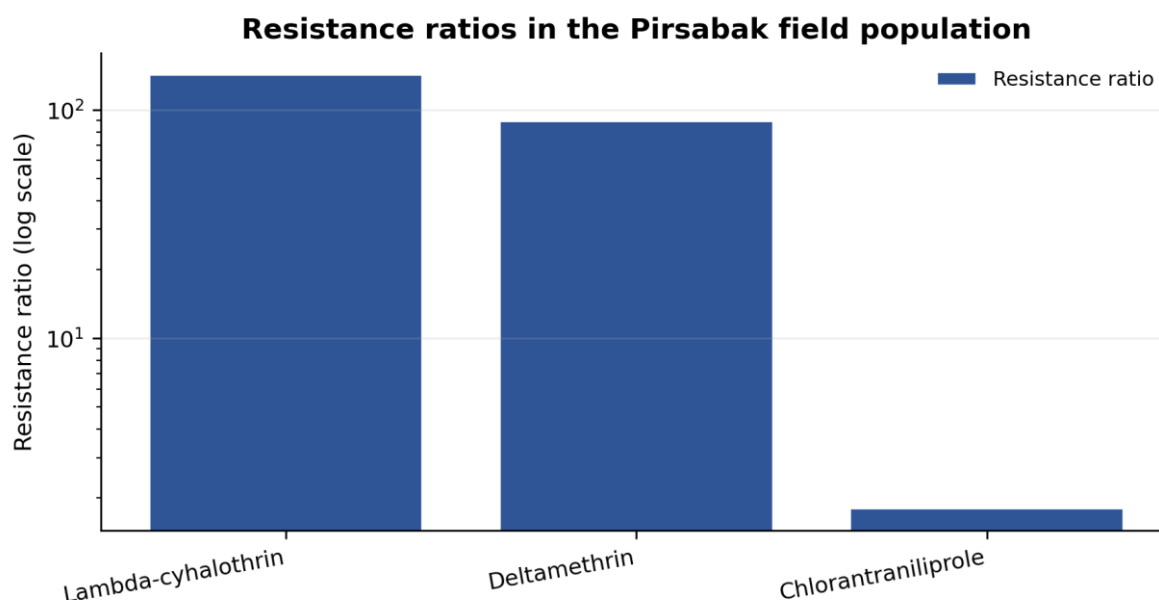
#### 3.1. Resistance and cross-resistance

The Pirsabak population showed a 142.6-fold resistance ratio to lambda-cyhalothrin and an 89.4-fold ratio to deltamethrin. The chlorantraniliprole ratio was 1.8. The shallower pyrethroid slopes in the field population are consistent with greater heterogeneity, although raw mortality counts are required to confirm the models.

**Table 1. LC<sub>50</sub> values and resistance ratios**

| Insecticide         | Susceptible LC <sub>50</sub> | Field LC <sub>50</sub> | RR    | Supplied 95% CI |
|---------------------|------------------------------|------------------------|-------|-----------------|
| Lambda-cyhalothrin  | 0.28 ppm                     | 39.9 ppm               | 142.6 | 121.4–167.5     |
| Deltamethrin        | 0.42 ppm                     | 37.6 ppm               | 89.4  | 76.8–104.2      |
| Chlorantraniliprole | 0.15 ppm                     | 0.27 ppm               | 1.8   | 1.4–2.3         |

RR = field LC<sub>50</sub> / susceptible LC<sub>50</sub>. Confidence intervals are supplied values.

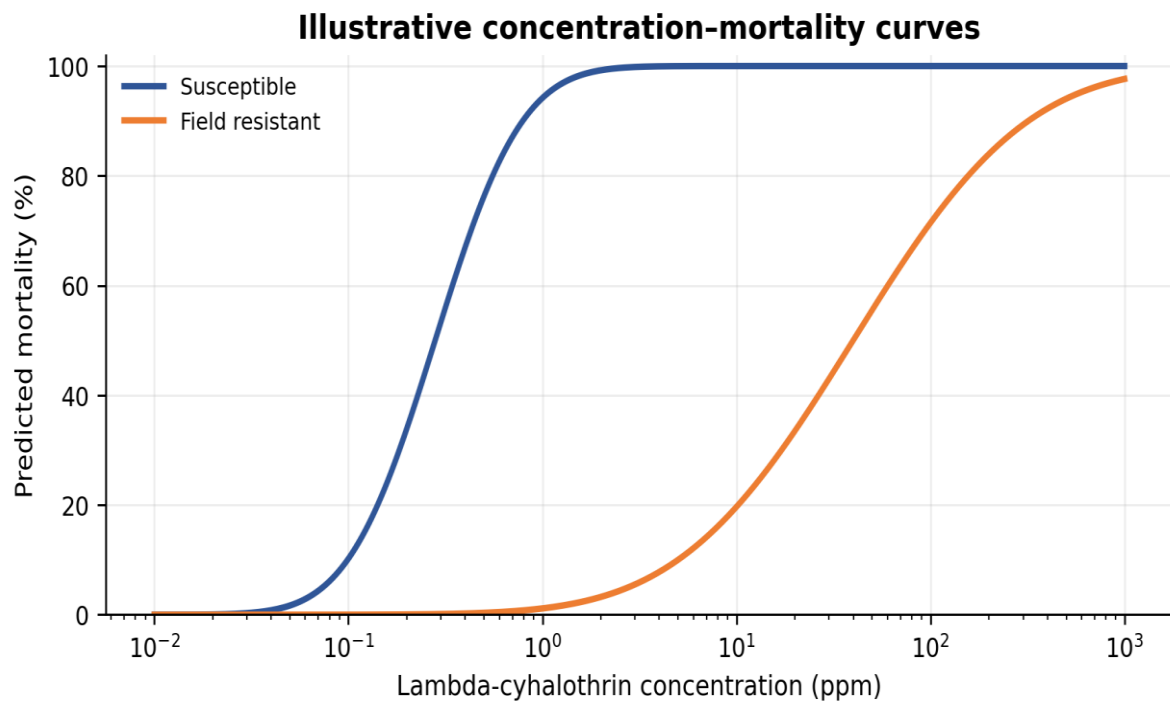


**Figure 1. Resistance ratios displayed on a logarithmic scale.**

**Table 2. Supplied probit parameters**

| Insecticide        | Strain          | Slope $\pm$ SE  | $\chi^2$ | df | P     |
|--------------------|-----------------|-----------------|----------|----|-------|
| Lambda-cyhalothrin | Susceptible     | 2.84 $\pm$ 0.23 | 3.42     | 4  | 0.491 |
| Lambda-cyhalothrin | Field resistant | 1.42 $\pm$ 0.18 | 5.18     | 4  | 0.269 |
| Deltamethrin       | Susceptible     | 2.61 $\pm$ 0.21 | 4.21     | 4  | 0.378 |
| Deltamethrin       | Field resistant | 1.38 $\pm$ 0.17 | 4.92     | 4  | 0.295 |

The model cannot be audited without concentration-specific deaths, totals, and control mortality.

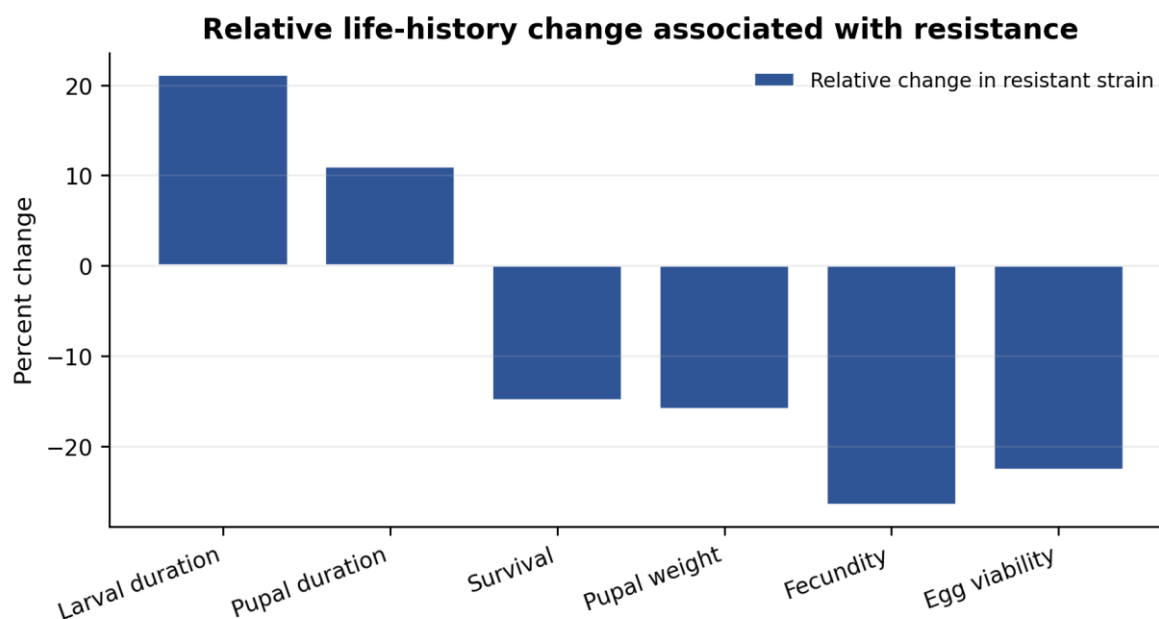


**Figure 2. Illustrative lambda-cyhalothrin concentration–mortality curves reconstructed from supplied LC<sub>50</sub> and slope values.**

### 3.2. Fitness costs

**Table 3. Life-history traits of susceptible and resistant strains**

| Parameter            | Susceptible   | Resistant     | Correct interpretation | Reported P |
|----------------------|---------------|---------------|------------------------|------------|
| Larval development   | 11.8 ± 0.4 d  | 14.3 ± 0.5 d  | 21.2% longer           | 0.001      |
| Pupal development    | 8.2 ± 0.3 d   | 9.1 ± 0.4 d   | 11.0% longer           | 0.048      |
| Survival to pupation | 92.4 ± 2.1%   | 78.6 ± 3.0%   | 14.9% lower            | 0.002      |
| Pupal weight         | 33.4 ± 1.2 mg | 28.1 ± 1.1 mg | 15.9% lower            | 0.003      |
| Fecundity            | 847 ± 28 eggs | 623 ± 24 eggs | 26.5% lower            | <0.001     |
| Egg viability        | 94.6 ± 1.8%   | 73.2 ± 2.4%   | –21.4 points; –22.6%   | <0.001     |



**Figure 3. Relative changes in life-history traits of the resistant population. Positive bars indicate longer development; negative bars indicate reduced performance.**

Composite interpretation: Survival, fecundity, and egg viability were all lower in the resistant population, but a formal relative-fitness index requires complete life-table data, independent colony replicates, and population growth-rate estimation.

**Table 4. Resistance-management interpretation of the supplied toxicological evidence**

| Insecticide         | Evidence from supplied data                                    | Resistance-management implication                                                        | Verification required                                       |
|---------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------|
| Lambda-cyhalothrin  | RR = 142.6; strong performance costs in field strain           | Suspend routine use where resistance is confirmed; do not rotate with another pyrethroid | Raw dose-mortality records; local diagnostic concentration  |
| Deltamethrin        | RR = 89.4; pattern consistent with pyrethroid cross-resistance | Treat as the same resistance group as lambda-cyhalothrin                                 | Mechanism assays and field-efficacy confirmation            |
| Chlorantraniliprole | RR = 1.8 in the supplied comparison                            | Potential rotation option only if local susceptibility remains high                      | Current baseline, label compliance, and repeated monitoring |

**Table 5. Minimum evidence required for publication-grade resistance assessment**

| Dataset              | Minimum required fields                                                     | Purpose                                              |
|----------------------|-----------------------------------------------------------------------------|------------------------------------------------------|
| Bioassay             | Dose, replicate, insects exposed, dead/alive, control mortality, assay date | Reproduce probit models and confidence intervals     |
| Colony history       | Collection site, host, generation, rearing conditions, prior exposure       | Interpret strain comparability and selection history |
| Life history         | Individual or cohort survival, development, mass, fecundity, hatch          | Estimate relative fitness and uncertainty            |
| Resistance mechanism | Synergist assays, enzyme activity, target-site genotype                     | Distinguish metabolic and target-site resistance     |
| Field validation     | Product, rate, spray conditions, pest density, damage, yield                | Link laboratory resistance with operational control  |

### 3.3. Integrated interpretation

The contrast among insecticides was pronounced. Resistance ratios above 80 for both pyrethroids indicate that substantially higher concentrations were required for the field population than for the susceptible strain, whereas the 1.8-fold chlorantraniliprole ratio was close to the reference response. The lower slopes for the field population are also consistent with

greater phenotypic heterogeneity. This combination of a large LC<sub>50</sub> shift and a shallow slope is operationally concerning because a field dose may kill the most susceptible individuals while leaving a variable resistant fraction.

Fitness-associated differences occurred across several stages rather than in a single endpoint. Larval development was 21.2% longer, pupal development was 11.0% longer, survival to pupation was 14.9% lower and pupal mass was 15.9% lower in the resistant population. Reproductive performance showed the largest proportional decline, with 26.5% fewer eggs and a 21.4-percentage-point reduction in hatch. The consistency of direction strengthens the interpretation of a resistance-associated cost, although colony origin and genetic background remain potential alternative explanations.

#### 4. Discussion

The results support a mode-of-action interpretation rather than a product-name interpretation. Replacing lambda-cyhalothrin with deltamethrin would retain selection within the same target-site class and would be unlikely to restore reliable control where cross-resistance is present. Pakistani surveys have likewise shown multiple resistance to formulated pyrethroids and other insecticides in *H. armigera*, reinforcing the need for local diagnostic doses and resistance-ratio tracking rather than calendar-based chemical substitution (Qayyum et al., 2015).

The apparent susceptibility to chlorantraniliprole provides a potential management option, but it also creates a stewardship risk. When one class remains effective after pyrethroid failure, growers may increase its frequency, shorten intervals or combine it with unnecessary partners. Such concentration of selection can erode the remaining option. A defensible programme should rotate genuinely different IRAC groups across pest generations, limit the number of applications per crop, preserve untreated intervals and integrate biological, cultural and monitoring-based tactics (Sparks & Nauen, 2015; Heckel, 2012).

Fitness costs could contribute to resistance decline if pyrethroid selection is relaxed, but the observed differences should not be converted directly into a predicted field reversion rate. The resistant and susceptible colonies may differ at loci unrelated to resistance, and laboratory rearing can magnify founder effects. Reciprocal crosses, backcrosses or near-isogenic lines would help separate resistance effects from background effects. Multi-generation competition experiments without insecticide would provide a stronger estimate of whether susceptible alleles increase over time (Roush & McKenzie, 1987; Bird et al., 2020).

Host plant is another source of variation. Tomato chemistry and nutritional quality can alter development, detoxification demand and reproductive output, and the same resistant genotype may express a different cost on cotton or an artificial diet. The present findings are therefore most directly applicable to the tomato-based rearing conditions described. Testing additional host plants and temperatures would clarify whether the observed cost is robust across the environments encountered by this highly mobile pest (Fitt, 1989; Mbuji et al., 2024).

For surveillance, the most useful next step is a repeated regional programme using the same susceptible reference, bioassay method and diagnostic concentrations. Sampling before and after the main spray period would show whether resistance frequency changes within a season. Linking toxicological results to field-control records, enzyme assays and target-site genotyping would identify whether management failure is driven by metabolic resistance, sodium-channel mutations, reduced penetration or a combination of mechanisms (ffrench-Constant, 2013; Li et al., 2007).

Resistance-monitoring results become actionable only when they are linked to field performance. A large laboratory resistance ratio signals elevated risk, but control failure also depends on application rate, coverage, larval stage, temperature, formulation and the concentration that can be maintained on the crop. Diagnostic-dose assays should therefore be repeated during the season and paired with post-application counts in treated fields. When survivors are detected after a correctly applied pyrethroid treatment, they should be collected for confirmatory bioassay rather than immediately exposed to another pyrethroid. This feedback loop distinguishes operational resistance from poor application and helps prevent repeated selection against the same resistant fraction (Denholm & Rowland, 1992; Robertson et al., 2007).

Mechanistic work would strengthen interpretation of the cross-resistance pattern. Synergist bioassays can indicate whether oxidases, esterases or glutathione-associated enzymes contribute to the phenotype, while sequencing or expression assays can test target-site and metabolic candidates. Such tests must be interpreted cautiously because association does not prove that a specific allele or transcript explains the entire resistance ratio. The shallower field-population slopes suggest heterogeneity, so several mechanisms or genotype classes may be present simultaneously. Establishing isofemale lines and comparing their toxicological and molecular profiles would separate within-population variation from assay noise and would clarify whether the apparent fitness costs co-segregate with resistance (ffrench-Constant, 2013; Li et al., 2007; Scott, 1999).

Management also needs a landscape perspective. Adults can move between tomato, cotton and other hosts, meaning that selection imposed in one crop can affect susceptibility in the next. Coordination among neighbouring growers is therefore more effective than isolated product changes within a single field. Shared monitoring dates, agreement on mode-of-action windows

and removal of heavily infested crop residues can reduce asynchronous exposure. Non-chemical mortality from natural enemies, sanitation and timely harvest should be treated as part of the resistance-management programme because each reduces the number of larvae exposed to insecticides. The objective is not complete avoidance of chemistry, but fewer, better-timed applications that retain effective doses while reducing the frequency of selection events (Fitt, 1989; Sparks & Nauen, 2015).

The fitness comparison should be repeated across generations and genetic backgrounds before it is used to predict resistance decline. Laboratory colonisation can itself reduce development or reproduction, and the susceptible strain may differ from the field population at many loci unrelated to resistance. Reciprocal crosses, near-isogenic lines or selection-and-relaxation experiments would provide stronger evidence. A complete demographic analysis should estimate net reproductive rate, generation time and intrinsic rate of increase, with uncertainty propagated across component traits. The supplied data nevertheless identify a coherent set of performance disadvantages that are relevant to management: longer development can increase exposure to mortality, lower survival reduces adult recruitment, and reduced fecundity and hatch can slow population growth when pyrethroid selection is absent (Roush & McKenzie, 1987; Bird et al., 2020; Mbuji et al., 2024).

An operational response matrix should specify what happens after each monitoring result. Confirmed high pyrethroid resistance should trigger suspension of lambda-cyhalothrin and deltamethrin, review of recent applications, and selection of a genuinely different mode of action only when the pest threshold is exceeded. Borderline results should prompt repeat sampling rather than automatic escalation of dose. After any alternative treatment, larval survival should be checked within the expected activity window and recorded with weather and coverage information. At the end of the season, susceptibility data, treatment history and field performance should be reviewed together to plan the next crop. This documented sequence makes resistance management auditable and reduces the common practice of responding to failure with shorter intervals or mixtures that intensify selection (Denholm & Rowland, 1992; Sparks & Nauen, 2015).

Recent resistance studies reinforce that fitness costs and cross-resistance can depend on the selected compound and host context; therefore, resistance ratios should be interpreted together with inheritance, life-history, and host-plant evidence (Bird et al., 2020; Mbuji et al., 2024).

The lambda-cyhalothrin ratio indicates very high resistance under the supplied assay conditions and is consistent with the long history of pyrethroid selection in *H. armigera* (Kranthi et al., 2001). Comparable resistance patterns have been reported in geographically distinct populations, demonstrating that local monitoring is essential (Torres-Vila et al., 2002).

The high deltamethrin ratio supports cross-resistance within the pyrethroid group rather than independent susceptibility to each compound (Ahmad et al., 2008). Shared target-site and metabolic mechanisms can make product rotation ineffective when both compounds impose similar selection (Li et al., 2007).

The chlorantraniliprole ratio of 1.8 suggests little cross-resistance in this sample, but it should not be interpreted as permission for repeated diamide use (Sparks & Nauen, 2015). Resistance evolution can accelerate when one effective alternative becomes the dominant replacement for a failed chemical class (Heckel, 2012). The shallower field-population slopes suggest heterogeneous susceptibility and potentially multiple alleles, mechanisms, or recent migrants within the colony (Walsh et al., 2018). Without concentration-specific mortality data, however, the reconstructed curves remain descriptive rather than evidentiary (Robertson et al., 2007). Slower development and reduced reproduction are compatible with a cost of resistance and resemble trade-offs observed after laboratory selection in *H. armigera* (Cui et al., 2018). Recovery of susceptibility remains conditional on reduced pyrethroid selection, migration of susceptible alleles, and absence of compensatory evolution (Gassmann et al., 2009).

## 5. Conclusion

The supplied dataset indicates very high lambda-cyhalothrin resistance, high cross-resistance to deltamethrin, and little cross-resistance to chlorantraniliprole. Resistance was associated with slower development and reduced survival, pupal weight, fecundity, and egg viability. These costs create a potential opportunity for susceptibility recovery only when pyrethroid selection pressure is genuinely reduced and susceptible alleles can persist or immigrate.

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## 6.2. Conflict of Interest

The authors declare no conflict of interest.

## 6.3. Author Contributions

All authors Contributed Equally.

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