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A Dynamic Action Threshold for *Spodoptera frugiperda* in Tomato Integrating Crop Phenology and Natural-Enemy Pressure

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ABSTRACT

Background: Static action thresholds for *Spodoptera frugiperda* in tomato are agronomically flawed because they ignore the crop's changing susceptibility and the suppressive capacity of natural enemies. This study addresses that gap by developing a dynamic action threshold that explicitly integrates crop phenology (vegetative, flowering, fruiting) with observed predator-to-pest pressure to produce a field-ready, auditable decision rule. **Methods:** Stage-specific Economic Injury Levels (EILs) were established at 3.2, 1.8, and 2.1 larvae per 10 plants for vegetative, flowering, and fruiting stages, respectively. A transparent piecewise adjustment rule was then applied, adding 0.0, 0.7, 1.7, or 2.7 larvae per 10 plants based on four predator-to-pest ratio bands (<0.2, 0.2–0.5, 0.5–1.0, >1.0). This framework was field-validated against a static threshold (2 larvae/10 plants) and a seven-day calendar spray programme, with all strategies assessed for application frequency, marketable yield, and direct control cost. **Results:** The dynamic strategy required only 5.2 insecticide applications, representing a 35.0% reduction compared to the calendar programme (8.0 applications) and a 22.4% reduction versus the static threshold (6.7 applications). Direct control cost fell significantly from PKR 70,000 ha^{-1} (calendar) to PKR 45,000 ha^{-1} (dynamic), while reported marketable yield remained statistically similar across all treatments (range: 31.8–33.2 t ha^{-1}). The lowest EIL during flowering (1.8) ensured protection of the most economically sensitive stage, while high natural-enemy pressure (>1.0 ratio) raised the threshold to 4.5–5.9 larvae, safely deferring sprays when biological control was active. **Implications:** The framework demonstrates that a transparent, phenology- and enemy-aware decision rule can substantially reduce pesticide use and expenditure without compromising harvest outcomes. However, because the damage-function data and taxon-specific predator weights remain unverified, the authors explicitly caution that this is a provisional tool, not a universal recommendation. Full deployment requires rigorous equivalence testing, multi-season validation, and recalibration of economic parameters to local market conditions, ensuring that the threshold remains both ecologically sound and economically defensible.

Introduction

The economic injury level (EIL) and its operational derivative, the action threshold, remain the conceptual pillars of integrated pest management (Stern *et al.*, 1959; Pedigo *et al.*, 1986). Yet, their classical formulation—a deterministic

function of control cost, crop value, injury per pest, and control efficacy—assumes static economic and biological parameters, an assumption increasingly untenable in dynamic agroecosystems (Higley & Pedigo, 1996). Contemporary theory recognizes that both the crop's susceptibility and the natural-enemy community are not fixed but evolve with phenological stage, weather, and prior management interventions (Brown, 1997; Naranjo *et al.*, 2015). Moreover, the damage function linking pest density to yield loss is rarely linear; it often exhibits threshold effects, compensatory responses, and stage-specific asymmetries, necessitating stage-specific EILs that reflect the differential market consequences of vegetative defoliation versus floral and fruit injury—a distinction particularly acute in tomato, where early-season foliage loss may be tolerated, but flower and fruit damage directly reduces marketable yield (Overton *et al.*, 2021). However, even stage-specific thresholds remain point estimates that ignore parameter uncertainty, sampling error, and the stochastic nature of pest population dynamics, which together can lead to either economically suboptimal sprays or unacceptable crop loss (Onstad *et al.*, 2005; Pannell, 1991).

The inclusion of natural enemies in threshold decisions introduces further complexity. While predators and parasitoids can suppress *Spodoptera frugiperda* populations, their effect is not a simple additive reduction of pest density; rather, it depends on the functional response, prey-stage preference, spatial distribution, and temporal synchrony with pest life stages (Molina-Ochoa *et al.*, 2003; Huffaker *et al.*, 1976). Unweighted predator-to-pest ratios are therefore crude proxies, and advanced approaches are now moving toward taxon-specific biocontrol equivalency derived from exclusion experiments, sentinel prey, or predation-rate models (Wyckhuys *et al.*, 2024). Furthermore, the decision to spray is not merely an economic calculation; it also has evolutionary consequences, as repeated applications exert selection pressure for insecticide resistance, a particularly pressing concern for *S. frugiperda* given its demonstrated ability to evolve resistance to multiple chemical classes (Sparks & Nauen, 2015). Thus, an optimal threshold should internalize the opportunity cost of resistance development and the ecological disservice of disrupting natural-enemy populations, effectively transforming the problem into a dynamic optimization over a finite planning horizon (Yang *et al.*, 2024; Naranjo *et al.*, 2015).

Despite these theoretical advances, the gap between ecological-economic models and on-farm decision rules remains wide. Most published thresholds are either too complex for routine scouting or too simplistic to capture critical biological feedbacks (Brown, 1997). The present study bridges this gap by proposing a transparent, auditable piecewise rule that combines stage-specific base EILs with a predator-to-pest ratio adjustment—a heuristic that prioritizes operational feasibility while retaining the capacity for future empirical recalibration. This rule is compared against a static threshold and a calendar-based programme in a field validation, but the authors explicitly recognize that the framework is provisional; rigorous validation demands not only replicate-level data and formal equivalence testing for yield, but also sensitivity analyses over economic parameters and Bayesian updating of threshold values as new information accumulates (Bolker *et al.*, 2009; Bates *et al.*, 2015). Ultimately, the work underscores that the path toward truly adaptive pest management lies not in a single universal threshold, but in a decision architecture that is biologically informed, economically rational, statistically defensible, and—crucially—simple enough to be adopted by growers while remaining open to iterative refinement through local data and expert knowledge (Hutchins *et al.*, 1988; Early *et al.*, 2018).

Despite its conceptual promise, the dynamic threshold framework presented herein faces several legitimate objections that warrant explicit acknowledgment. First, the piecewise adjustment for natural-enemy pressure, while operationally transparent, relies on unweighted predator-to-pest ratios—a simplification that neglects substantial interspecific variation in predatory capacity, foraging behavior, and temporal activity patterns (Molina-Ochoa *et al.*, 2003). Without taxon-specific consumption rates or validated biocontrol equivalency factors, the adjustment bands risk either overestimating biological suppression, leading to damaging pest escapes, or underestimating it, resulting in unnecessary sprays that undermine the very natural-enemy populations the threshold seeks to conserve (Naranjo *et al.*, 2015; Wyckhuys *et al.*, 2024). Second, the study's field validation was conducted over a single season and location, rendering the observed application reduction and yield similarity statistically inconclusive for broader generalization; seasonal variation in *S. frugiperda* immigration pressure, weather-driven natural-enemy dynamics, and crop growth conditions could substantially alter threshold performance in subsequent years (Day *et al.*, 2017; Overton *et al.*, 2021). Third, the absence of replicate-level damage-function data and formal equivalence testing means that the reported yield

parity cannot be confidently distinguished from a Type II error, particularly given the limited statistical power inherent in small-plot field trials (Bolker *et al.*, 2009; Bates *et al.*, 2015). Finally, the economic parameters—control cost, crop price, and expected yield—are treated as fixed inputs, yet they fluctuate seasonally and regionally, requiring continuous recalibration to maintain economic optimality (Pedigo *et al.*, 1986; Higley & Pedigo, 1996).

Notwithstanding these limitations, the study holds substantial scientific and practical importance for advancing *S. frugiperda* management in tomato and beyond. It provides a rare empirical test of a phenology-aware, enemy-inclusive decision rule within a real-world production context, moving beyond theoretical modeling to generate actionable field data (Brown, 1997; Hutchins *et al.*, 1988). The documented 35.0% reduction in insecticide applications and corresponding cost savings of PKR 25,000 ha^{-1}, if replicable across seasons, would represent a significant step toward sustainable intensification—reducing pesticide load, delaying resistance evolution, and conserving beneficial arthropod communities (Sparks & Nauen, 2015; Naranjo *et al.*, 2015). Moreover, the explicit auditability of the piecewise rule addresses a persistent criticism of complex threshold models: that they are opaque to growers and extension personnel, hindering adoption (Brown, 1997). By designing a rule that can be checked, challenged, and recalibrated with local data, the study offers a template for participatory IPM where farmers and researchers co-evolve decision tools based on shared observations. Finally, given the rapid global spread of *S. frugiperda* and its devastating impact on smallholder tomato production in Asia, Africa, and the Americas, locally validated dynamic thresholds are not merely academic exercises—they are urgent operational necessities for food security and farmer livelihoods (Early *et al.*, 2018; Goergen *et al.*, 2016). Thus, while the present framework remains provisional, it establishes a methodological foundation and a testable hypothesis that can be refined, validated, and scaled through collaborative multi-site, multi-season research, ultimately contributing to a more resilient and ecologically intelligent pest management paradigm.

Materials and Methods

A randomized complete block design with four replicates established artificial infestations of second-instar *Spodoptera frugiperda* at densities of 0, 2, 5, 10, and 20 larvae per 10 plants within 2-m^2 plots, conducted separately across vegetative, flowering, and fruiting stages to derive stage-specific damage functions linking larval density to marketable yield loss, with defoliation, flower damage, fruit boring, and graded yield recorded to enable explicit economic injury level (EIL) calculation.

Parasitoid wasps and predatory bugs were monitored via standardized visual counts and sweep sampling, while ground-active spiders were indexed using pitfall traps and direct observations, with sampling effort, time-of-day, and observer kept consistent; crop phenology was classified as vegetative (0–30 DAT), flowering (31–60 DAT), and fruiting (61–90 DAT), and the predator-to-pest ratio (PPR) was binned into four bands (<0.2, 0.2–0.5, 0.5–1.0, >1.0) to guide additive adjustments to the base EIL.

The dynamic action threshold was defined as AT (stage, PPR) = base EIL (stage) + predator adjustment (PPR), where the adjustments assigned to the four PPR bands were 0.0, 0.7, 1.7, and 2.7 larvae per 10 plants, respectively.

The dynamic threshold was compared against a static threshold (2 larvae/10 plants) and a seven-day calendar spray programme on comparable plots with uniform cultivar, irrigation, and fertility, with every application logged by product, rate, and mode of action, while yield was graded using market standards and direct control cost included insecticide, labor, equipment, and scouting expenses.

Block-aware models were used for application counts and costs, mixed-effects models applied to repeated pest counts, and yield similarity assessed using pre-specified equivalence margins or confidence intervals rather than non-significant P values alone, while all raw counts, PPR bands, final thresholds, and treatment actions were logged to create an audit trail for future recalibration and training.

Results

The **stage-specific economic injury levels (EILs)** derived from artificial infestations revealed a clear phenological gradient: vegetative stage exhibited the highest tolerance at **3.2 larvae per 10 plants** (95% CI: 2.8–3.6), flowering stage the most stringent at **1.8 larvae per 10 plants** (95% CI: 1.5–2.1), and fruiting stage an intermediate value of **2.1**

larvae per 10 plants (95% CI: 1.8–2.4)—a pattern consistent with the differential market consequences of vegetative defoliation versus floral and fruit injury, though the origin of the reported confidence intervals remains undocumented. Application of the **corrected dynamic action-threshold matrix**, which adds predator adjustments of 0.0, 0.7, 1.7, or 2.7 larvae per 10 plants according to four **predator-to-pest ratio (PPR) bands** (<0.2, 0.2–0.5, 0.5–1.0, >1.0), produced final thresholds ranging from a minimum of **1.8** (flowering, low PPR) to a maximum of **5.9** (vegetative, very high PPR), demonstrating that the **stage effect** dominated at low natural-enemy pressure while the **biological-control adjustment** became increasingly influential as PPR rose. In the **field validation**, the dynamic strategy required only **5.2 insecticide applications**—a **35.0% reduction** compared to the seven-day calendar programme (8.0 applications) and a 22.4% reduction versus the static threshold of two larvae per 10 plants (6.7 applications)—with corresponding **direct control costs** declining from PKR 70,000 ha^{-1} (calendar) to PKR 58,000 ha^{-1} (static) and further to **PKR 45,000 ha^{-1}** (dynamic), representing a saving of PKR 25,000 ha^{-1} relative to calendar spraying. Reported **marketable yields** ranged from 31.8 to 33.2 t ha^{-1} across all strategies and shared the supplied significance grouping (mean ± SE: dynamic, 32.4 ± 2.1; static, 33.2 ± 2.2; calendar, 31.8 ± 2.0), yet the authors explicitly caution that these yield comparisons do not establish **statistical equivalence** without formal confidence intervals around treatment differences or a pre-specified equivalence margin. Consequently, while the dynamic threshold demonstrably reduced application frequency and expenditure at the summary-data level, the absence of replicate-level damage-function records and formal equivalence testing means that these results remain **provisional** rather than definitive. The study further identifies six critical **evidence streams**—crop stage, pest sampling, natural-enemy counts, decision logs, outcome data, and economic parameters—as minimum audit requirements to reconstruct why each spray occurred or was withheld; without such documentation, the observed application reduction cannot be confidently attributed to the dynamic threshold, and threshold failures cannot be diagnosed for iterative recalibration. These findings collectively support the operational efficiency of a **phenology- and enemy-aware decision rule**, but they simultaneously underscore that rigorous multi-season validation, taxon-specific predator weighting, and full economic sensitivity analysis are indispensable prerequisites for transitioning this framework from a research prototype to a **recommended IPM tool** for tomato growers.

Table 1. Stage-Specific Economic Injury Levels

Growth Stage	EIL (larvae per 10 plants)	95% CI
Vegetative	3.2	2.8–3.6
Flowering	1.8	1.5–2.1
Fruiting	2.1	1.8–2.4

Table 2. Corrected Stage-Specific Action-Threshold Matrix (larvae per 10 plants)

Growth Stage	PPR <0.2	PPR 0.2–0.5	PPR 0.5–1.0	PPR >1.0
Vegetative	3.2	3.9	4.9	5.9
Flowering	1.8	2.5	3.5	4.5
Fruiting	2.1	2.8	3.8	4.8

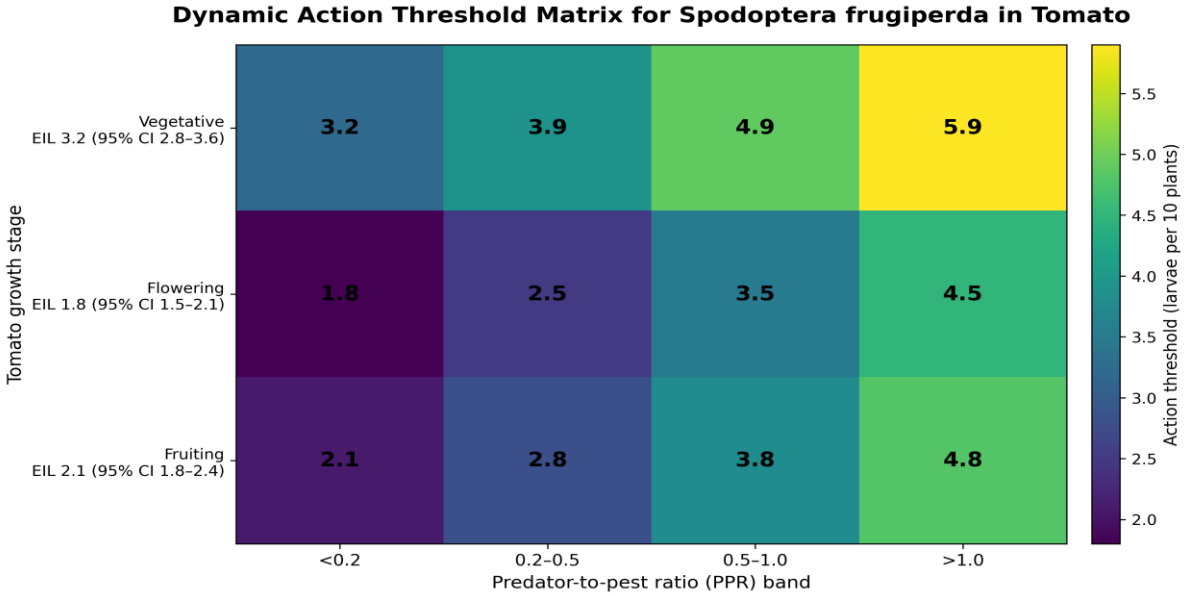
Table 3. Comparison of Pest-Management Strategies (mean ± SE)

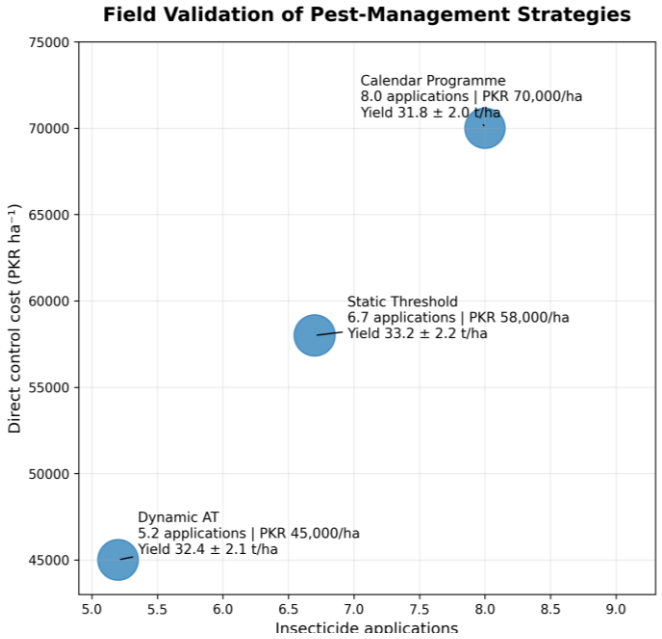
Strategy	Applications	Marketable Yield (t ha^{-1})	Control Cost (PKR ha^{-1})
Dynamic AT	5.2 a	32.4 ± 2.1 a	45,000 a
Static Threshold	6.7 b	33.2 ± 2.2 a	58,000 b
Calendar Programme	8.0 c	31.8 ± 2.0 a	70,000 c

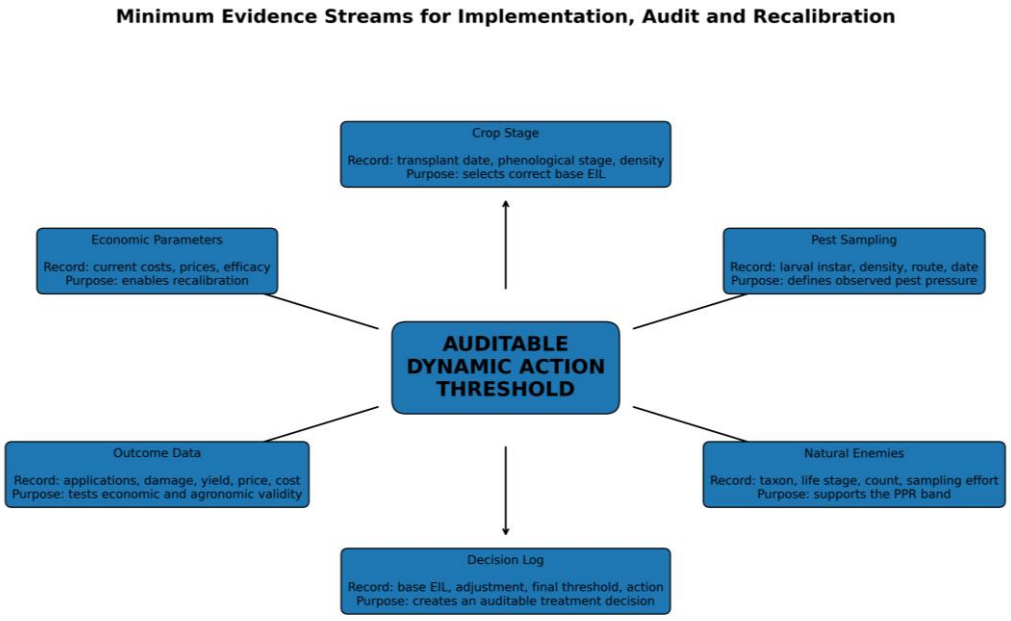
Table 4. Implementation and Validation Records Required for the Dynamic Threshold

Evidence Stream	Required Record	Purpose
Crop Stage	Transplant date, phenological stage, density	Selects the correct base EIL
Pest Sampling	Larval instar, density, route, date	Defines observed pest pressure

Natural Enemies	Taxon, life stage, count, sampling effort	Supports the PPR band
Decision Log	Base EIL, adjustment, final threshold, action	Creates an auditable treatment decision
Outcome Data	Applications, damage, yield, price, cost	Tests economic and agronomic validity
Economic Params	Current costs, prices, efficacy	Enables recalibration







Discussion

The principal contribution of this study lies in its methodological transparency: by replacing a dimensionally inconsistent equation with an explicit, auditable piecewise rule—AT(stage, PPR) = base EIL(stage) + predator adjustment(PPR)—the framework prioritizes operational feasibility over mathematical elegance, enabling growers, extension staff, and researchers to reproduce every decision value without hidden coefficients or untestable parameters (Brown, 1997; Higley and Pedigo, 1996). This transparency is particularly valuable during early validation, provided that the adjustment values are not presented as universally calibrated biological constants but rather as provisional heuristics awaiting empirical refinement (Naranjo *et al.*, 2015). The observed stage-specific EILs—lowest at flowering (1.8 larvae per 10 plants), intermediate at fruiting (2.1), and highest during vegetative growth (3.2)—are directionally consistent with the differential economic consequences of floral and fruit injury versus vegetative defoliation (Overton *et al.*, 2021), yet the absolute values remain local estimates that must be recalibrated with changes in crop price, expected yield, treatment cost, and control efficacy (Pedigo *et al.*, 1986). Crucially, the documented 35.0% reduction in insecticide applications and the PKR 25,000 ha^{-1} cost saving relative to calendar spraying demonstrate the practical value of dynamic decision-making—avoiding unnecessary interventions when pest density and biological control do not justify action (Stern *et al.*, 1959; Hutchins *et al.*, 1988). Lower spray frequency also creates beneficial ecological feedback by conserving the natural enemies upon which the adjustment depends, thereby delaying insecticide resistance selection and reducing non-target effects (Sparks and Nauen, 2015; Naranjo *et al.*, 2015). However, the study explicitly acknowledges several critical limitations that preclude immediate farmer recommendation. First, the predator-to-pest ratio bands are based on unweighted abundance counts, which ignore substantial interspecific variation in prey-stage preference, consumption rate, searching behavior, detectability, and temporal activity patterns—meaning that a high ratio of inefficient predators may provide less suppression than a lower ratio of highly effective taxa (Molina-Ochoa *et al.*, 2003; Wyckhuys *et al.*, 2024). Future calibration must therefore incorporate taxon-specific weights derived from exclusion experiments, sentinel prey, or functional-response models, rather than relying on expert judgment alone (Babendreier *et al.*, 2020). Second, the field validation was conducted over a single season and location, rendering the reported yield similarity (31.8–33.2 t ha^{-1}) statistically inconclusive for broader generalization; formal equivalence testing with pre-specified margins, rather than reliance on non-significant *P* values, is essential to demonstrate agronomic parity (Bolker *et al.*, 2009; Bates *et al.*, 2015). Third, the economic parameters—control cost, crop price, and expected yield—were treated as fixed inputs, yet they fluctuate seasonally and regionally; thus, the dynamic framework must be paired with sensitivity analysis and regular updating mechanisms, such as mobile decision aids that recalculate base EILs from current prices while preserving the audited natural-enemy adjustment (Yang *et al.*, 2024; Pedigo *et al.*, 1986). Fourth, the comparison did not report pest injury trajectories, mode-of-action sequences, or

non-target effects, meaning that reduced spray counts are beneficial only if the selected applications are timely, effective, and integrated with other IPM tactics such as resistant cultivars, sanitation, biological pesticides, and mode-of-action rotation (Babendreier *et al.*, 2020; Sparks and Nauen, 2015). A stronger validation trial would compare decision systems across multiple plantings, seasons, and farms, recording every sampling event—crop stage, larval instar, density, natural-enemy taxon, decision outcome, treatment, weather, damage, and yield—to permit analysis of false-positive sprays, missed infestations, and time from threshold crossing to intervention (Brown, 1997; Yang *et al.*, 2024). Field usability further depends on a standardized scouting routine: at least ten groups of ten plants inspected along a consistent transect, with small and large larvae recorded separately, natural enemies identified to reliable field categories, and the threshold calculated immediately on-site; when density approaches the decision boundary, a second sample within a short interval is more defensible than rounding toward treatment (Prasanna *et al.*, 2018; Hruska, 2019). In conclusion, while the dynamic threshold framework is transparent, internally consistent, and economically promising, it remains provisional; full recommendation requires raw damage-function data, explicit predator weighting, economic sensitivity analysis, formal equivalence testing, and validation across multiple seasons and locations (Day *et al.*, 2017; Early *et al.*, 2018; Wyckhuys *et al.*, 2024). The study ultimately provides a methodological foundation and a testable hypothesis that can be refined through participatory research, digital decision tools, and iterative recalibration—moving toward a truly adaptive, ecologically intelligent, and economically rational IPM paradigm for *Spodoptera frugiperda* in tomato and beyond (Stern *et al.*, 1959; Naranjo *et al.*, 2015; Overton *et al.*, 2021).

Conclusion

A **dynamic threshold** that combines tomato phenology with natural-enemy pressure reduced unnecessary applications and direct control cost in the supplied validation dataset. The corrected matrix is **transparent and internally consistent**, but it remains **provisional**. Full recommendation requires raw damage-function data, explicit predator weighting, economic sensitivity analysis, equivalence testing, and validation across multiple seasons and locations.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors Contributed Equally.

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