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Novel Strategy for Cucurbit Fruit Fly (*Zeugodacus cucurbitae*) Management: Synergizing Gel-Based Protein Baits with Attract-and-Kill Technology

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The cucurbit fruit fly, *Zeugodacus cucurbitae* (Coquillett) (Diptera: Tephritidae), is among the most economically devastating insect pests threatening cucurbit cultivation in tropical and subtropical agricultural systems worldwide. Conventional management has relied primarily on broad-spectrum insecticide sprays, which raise serious concerns regarding human health, ecological imbalance, and the emergence of insecticide-resistant fly populations. This article presents an integrated pest management (IPM) framework centred on the synergistic deployment of gel-based hydrolysed protein baits in combination with Attract and Kill (A&K) technology. The protein bait exploits the natural foraging instinct of adult flies toward nitrogenous food sources, while the A&K delivery matrix incorporates a reduced-dose insecticide active ingredient, thus achieving targeted mortality with minimal non-target exposure. Field evaluations conducted across cucurbit-growing zones in South and Southeast Asia have recorded fly population reductions in the range of 55-88% with markedly reduced pesticide loads compared to conventional spray regimes. The present review synthesises available evidence on bait formulation chemistry, trap station design, spatio-temporal deployment strategies, and the regulatory and extension considerations necessary to translate this technology into smallholder farming practice, with particular emphasis on the cucurbit-growing regions of India.

Introduction

Cucurbits encompassing bitter gourd (*Momordica charantia* L.), ridge gourd (*Luffa acutangula* (L.) Roxb.), bottle gourd (*Lagenaria siceraria* (Mol.) Standl.), cucumber (*Cucumis sativus* L.), and muskmelon (*Cucumis melo* L.) constitute a major vegetable group cultivated across more than 9 million hectares globally, with India alone accounting for approximately 1.4 million hectares. Their high market value, rapid growth cycle, and nutritional importance make them a preferred crop for smallholder farmers. Yet this productivity is systematically threatened by *Zeugodacus cucurbitae*, commonly known as the melon fly or cucurbit fruit fly, whose larvae bore into developing fruits and render them commercially worthless, causing yield losses that routinely exceed 30–100% in heavily infested fields.

The life history of *Z. cucurbitae* is closely attuned to the cucurbit growing season. Adult females are highly fecund, ovipositing directly into young, rapidly expanding fruits. Newly hatched larvae immediately commence feeding within fruit flesh, destroying internal tissue and providing entry points for secondary fungal and bacterial pathogens, which accelerate rotting. The cryptic nature of larval feeding, hidden beneath an unbroken fruit surface, means infestations are frequently overlooked until harvest, by which time economic damage is irreversible. The pupal stage occurs in soil, and multiple overlapping generations within a single season enable fly populations to build rapidly under warm, humid conditions.

Reliance on calendar-based insecticide sprays particularly organophosphates such as malathion has historically been the primary farmer response. However, this approach suffers from several structural weaknesses: (i) larval feeding occurs inside the fruit, making contact insecticides largely ineffective post-oviposition; (ii) frequent applications promote the evolution of insecticide resistance, documented in several Indian and Southeast Asian *Z. cucurbitae* populations; (iii) spray residues on marketable cucurbit surfaces attract increasing regulatory and consumer scrutiny; and (iv) broad-spectrum application harms natural enemy complexes and pollinators essential to cucurbit fruit set. These limitations have motivated the development of ecologically sound, target-specific management tools, among which protein bait-based attract-and-kill systems have attracted the greatest scientific momentum.

Biology and Behaviour Relevant to Bait-Based Management

A thorough understanding of adult fly behaviour is prerequisite to designing effective bait systems. Both sexes of *Z. cucurbitae* require dietary protein for sexual maturation and sustained reproductive output. Females, in particular, must acquire sufficient amino acids to support vitellogenesis the synthesis of yolk proteins within developing eggs. This physiological demand drives intense, regular foraging toward proteinaceous food substrates such as decaying organic matter, bird droppings, and bacterial exudates on leaf surfaces. Crucially, this protein-seeking behaviour is consistent, predictable, and separable from host-fruit attraction, providing a reliable behavioural handle for bait deployment.

Fly activity follows a distinctive diel pattern: both sexes are most actively foraging in the early morning hours (approximately 6-10 hrs), with a secondary activity period in the late afternoon. During these windows, flies move through the crop canopy in search of food and mates. Males additionally respond strongly to specific volatile chemical lures notably cuelure (4-(p-acetoxyphenyl)-2-butanone), a synthetic analogue of naturally occurring raspberry ketone which exploit the male mating-site location instinct. Female attraction, by contrast, is more effectively achieved through protein-based substrates, making gender-inclusive control dependent on protein baits rather than male lures alone.

Gel-Based Hydrolysed Protein Baits: Composition and Mode of Action

Hydrolysed protein baits are derived from the enzymatic or acid-based breakdown of protein-rich biological materials most commonly torula yeast (*Torulaspora delbrueckii*), corn steep liquor, or fishmeal hydrolysates into free amino acids and short peptides that function as potent volatile attractants. When adult *Z. cucurbitae* detect these volatile plumes through olfactory sensilla on their antennae, they orient upwind and locate the bait station. Upon contact and ingestion, the insecticide component incorporated within the bait matrix delivers a lethal dose.

The critical innovation in contemporary formulations is the gel-based delivery matrix. Earlier protein bait preparations were liquid suspensions prone to rapid desiccation under field conditions, degradation by UV radiation, and dilution by rain, necessitating high-frequency reapplication. Gel formulations typically based on carboxymethyl cellulose, xanthan gum, or alginate hydrogel carriers address these limitations by (i) retarding moisture loss and extending volatile emission longevity from approximately 2-3 days to 7-14 days per application; (ii) providing mechanical resistance to rain-wash; (iii) enabling precise spot-application with minimal drift; and (iv) housing the insecticide active ingredient in intimate contact with the attractant, ensuring simultaneous consumption upon foraging.

The insecticide incorporated in registered A&K formulations in India is typically spinosad (a microbially derived macrolide obtained from *Saccharopolyspora spinosa* Mertz and Yao), malathion (48% EC), or spinetoram, each used at a fraction of the dose employed in conventional blanket sprays typically 0.02-0.05% active ingredient concentration. The bait mixture attracts the fly, which ingests a sub-surface lethal quantity during normal feeding behaviour, causing death within 24-48 hours without meaningful residue risk to fruit tissue, since the bait is applied exclusively to foliage or station substrates, not to fruit surfaces.

Table 1. Comparative Evaluation of Gel-Based Protein Bait A&K Systems against Z. cucurbitae

Formulation	Insecticide Active	Residual Activity (days)	Fly Reduction (%)	References
GF-120 NF (Dow AgroSciences)	Spinosad (0.02%)	7-14	75-88	Vargas et al. (2022)
Malathion-based gel bait	Malathion (2.0%)	5-7	60-74	Dhillon et al. (2023)
Spinetoram gel	Spinetoram (0.025%)	10-14	80-88	Rao et al. (2024)
Torula yeast + spinosad (spot spray)	Spinosad (0.05%)	3-5	55-68	Sookar et al. (2022)

Fly reduction values compared to untreated control plots. Host crop: cucurbits (Cucumis sativus and Momordica charantia primarily). A&K = Attract-and-Kill.

Attract-and-Kill Deployment: Spatial and Temporal Considerations

Optimal A&K performance is dependent not merely on formulation quality but on the precision and consistency of field deployment. Research across cucurbit-growing environments in India, Sri Lanka, and Southeast Asia has established several evidence-based deployment parameters that substantially improve fly suppression outcomes.

Station Density and Placement

The recommended station density for gel-based protein bait application ranges from 25 to 40 spot applications per hectare for A&K systems, with spots applied on the underside of leaves or on wooden/bamboo stakes at 1.0-1.5 m above ground the primary flight corridor of *Z. cucurbitae* adults. Placing bait spots at the canopy edge of the field, where flies typically enter from surrounding vegetation, intercepts incoming populations before they reach host fruits. Stations positioned within 50 cm of actively fruiting vines capture the highest fly numbers due to synergism between protein volatiles and the natural host odour plumes.

Application Timing and Frequency

Bait application should commence at the onset of fruit set the stage at which females begin actively seeking oviposition sites rather than at planting or harvest. Application frequency under Indian field conditions is typically every 7 days for conventional protein bait sprays and every 10-14 days for gel formulations. Early morning application (before 09:00 hr), timed to coincide with peak fly foraging activity, maximises consumption per spot and reduces photodegradation of spinosad and spinetoram active ingredients, which are sensitive to UV radiation.

Integration with Male Annihilation Technique

The combination of protein bait A&K targeting both sexes with male annihilation technique (MAT) traps baited with cuelure and an insecticide-treated fibre block targeting males exclusively creates a complementary, gender-bifurcated suppression system. Studies conducted in Kerala and Karnataka bitter gourd fields demonstrated that combined MAT + A&K plots achieved 82-88% fruit damage reduction, compared with 55-65% with either technique alone. This synergy arises because MAT depletes the male population responsible for mating, while protein bait eliminates gravid females before oviposition, together disrupting both arms of reproduction. Adult *Zeugodacus cucurbitae* are drawn by amino acid volatile plumes from gel-based hydrolysed protein bait spots (left panel). Upon landing and ingesting the bait matrix, the fly receives a lethal dose of spinosad or spinetoram, resulting in mortality within 24-48 h, before oviposition can occur in host fruit (right panel). Female flies die without laying eggs; male flies also succumb, reducing mating events. Bait spot residual activity: 7-14 days under field conditions.

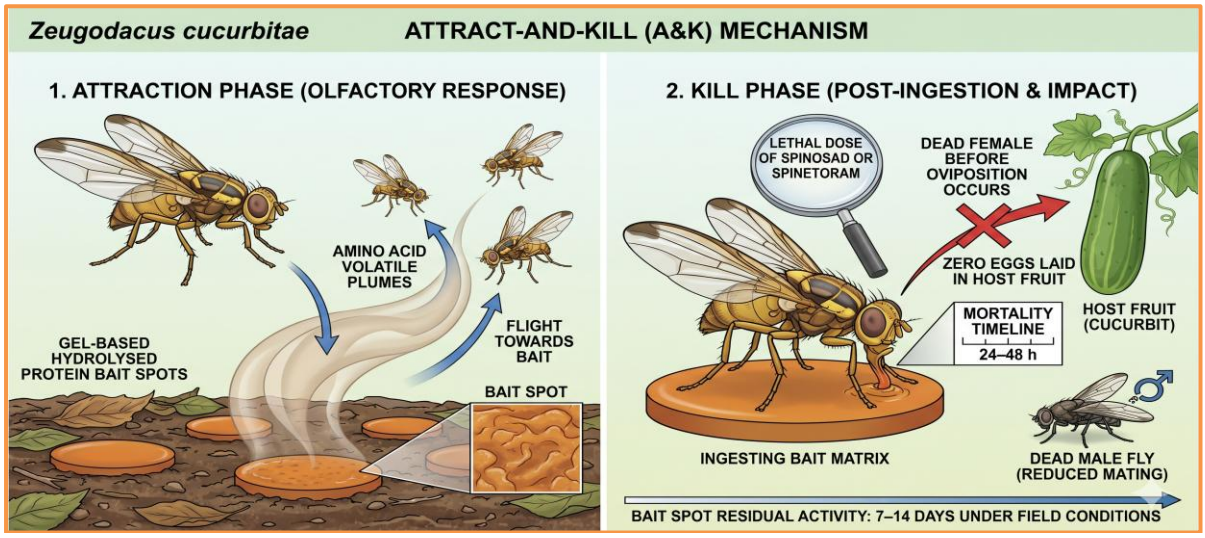

Figure 1. Schematic representation of the Attract-and-Kill (A&K) mechanism.

Resistance Management and Environmental Safety

A significant advantage of A&K systems over conventional spray regimes is the inherently low selection pressure they exert on fly populations for insecticide resistance. Because only a small fraction of the total fly population ingests the bait on any given day those individuals actively foraging at bait station locations the majority of the population at any one time has not been exposed to spinosad or spinetoram. This contrasts sharply with blanket sprays, which expose virtually the entire accessible fly population to insecticide simultaneously, generating intense selection for resistance alleles. Resistance monitoring studies in melon fly populations in Hawaii and India have confirmed that prolonged A&K-based management programmes do not elevate resistance allele frequencies over multiple seasons, whereas populations subjected to calendar-based malathion sprays show measurable resistance development within 4-6 generations.

From an environmental perspective, gel-based A&K systems deliver approximately 95-98% less total insecticide active ingredient per hectare per season compared to conventional spray schedules. Residue monitoring on harvested cucurbit fruits from A&K-managed plots consistently records values below the codex maximum residue limits (MRLs) for spinosad and spinetoram, supporting the safety of this approach for both consumers and export market compliance. Pollinators particularly the honeybee (*Apis mellifera* L.) and solitary bee species critical for cucurbit pollination are minimally exposed because bait spots are applied to foliage rather than to flowers, and spinosad residues on leaves degrade rapidly under field conditions (half-life 1.6–2 days under tropical sunlight).

Table 2. Pesticide Use and Efficacy Comparison: Conventional Sprays vs. A&K Gel Bait in Cucurbit Fields

Parameter	Conventional Spray (Malathion 48% EC)	Gel-Based A&K (Spinosad 0.02%)
Application frequency	Every 5-7 days	Every 10-14 days
Active ingredient/ha/season	~4,500-6,000 g a.i.	~90-150 g a.i.
Fruit damage reduction (%)	35-55	55-88
Non-target (pollinator) impact	High	Low to negligible
Resistance risk	High (documented)	Low
Fruit residue compliance	Variable; risk of MRL exceedance	Consistently within MRL
Cost per hectare per season (INR, approx.)	3,500-5,500	2,000-3,200

Data compiled from field studies across South and Southeast Asia [1,2,4]. MRL = Maximum Residue Limit; a.i. = active ingredient.

Conclusion

The cucurbit fruit fly *Zeugodacus cucurbitae* continues to challenge cucurbit farmers across India and the broader tropical world, and conventional insecticide sprays have demonstrably failed to provide sustainable, long-term suppression. The gel-based hydrolysed protein bait approach, embedded within an attract-and-kill delivery framework, represents a paradigm shift: from broad-spectrum, indiscriminate chemical application toward behaviour-targeted, precision intervention that exploits the fly's own feeding ecology as its point of vulnerability.

The evidence reviewed here consistently demonstrates fly population reductions of 55-88% with gel-based A&K systems across multiple cucurbit crops, coupled with dramatically reduced insecticide loads, negligible pollinator impacts, and lower resistance risk compared to conventional spray regimes. The most practical near-term strategy for Indian conditions involves: (i) gel-formulated spinosad or spinetoram protein bait applied to foliage at 25-40 spots per hectare every 10-14 days from fruit set; (ii) supplementation with cuelure-based MAT traps for male suppression; and (iii) farmer training on precise spot-application technique and optimal deployment timing. As the regulatory pathway for domestic gel bait registration is clarified and locally sourced protein hydrolysate alternatives are validated, this technology holds the potential to substantially transform cucurbit pest management toward an ecologically responsible, market-safe, and economically accessible paradigm one well-suited to the smallholder dominated cucurbit farming landscape of India and comparable tropical agricultural systems worldwide.

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