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Optimization of LED light traps enhances pest selectivity and energy efficiency in shallot agroecosystems

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ABSTRACT

Artificial light traps are crucial for pest monitoring, but their ecological impact and efficiency depend heavily on the light spectrum. This study evaluated the spectral effectiveness, ecological selectivity, and energy efficiency of light-emitting diode (LED) traps for managing major shallot pests in a tropical agroecosystem in South Sulawesi, Indonesia. A randomized block design field experiment with three replications was conducted to test three LED spectra: white (380–700 nm), yellow (570–590 nm), and purple (380–750 nm). Insect capture rates, ecological selectivity indices, and energy consumption were analyzed using ANOVA and Tukey's HSD test. The results demonstrated that LED color significantly influenced both total insect capture and species-specific attraction. White LEDs recorded the highest total insect abundance but exhibited low target specificity. In contrast, yellow LEDs demonstrated superior selectivity for key sucking pests, specifically *Thrips tabaci* and *Aphis gossypii*, achieving the highest Target Selectivity Percentage (TSP) and Ecological Safety Index (ESI). While white LEDs showed the highest overall capture efficiency per watt-hour, yellow LEDs were more energy-efficient per target pest captured. These findings conclude that wavelength-specific yellow LED traps offer a highly selective, ecologically safe, and energy-efficient tool for integrated pest management (IPM) programs in shallot cultivation.

Key words: Ecological safety, Energy efficiency, Integrated pest management, LED trap, Phototaxis

INTRODUCTION

Sustainable pest management has become a global priority due to increasing insecticide resistance, environmental contamination, and biodiversity decline (Abhilash and Singh, 2025; Muñoz-Bautista *et al.,* 2025; Zhou *et al.,* 2024). Vegetable production systems, including shallot (*Allium cepa* var. aggregatum), remain highly dependent on chemical insecticides, accelerating resistance development and disrupting agroecosystem balance. Major shallot pests include *Spodoptera exigua*, *Thrips tabaci*, and *Aphis gossypii*, which significantly reduce yield and quality.

The urgency of this research stems from the escalating ecological and economic costs associated with synthetic insecticide overuse in tropical shallot production. While conventional light traps have been used as a physical control alternative, broad-spectrum lighting often indiscriminately captures beneficial insects, thereby driving non-target insect decline and biodiversity disruption (van Langevelde et al., 2011; Baik *et al.,* 2026; Gaston *et al.,* 2012; Marangoni *et al.,* 2022). Therefore, there is an immediate need to transition toward selective, target-specific, and energy-efficient optical control technologies.

Light-based trapping systems exploit insect phototaxis and wavelength-specific visual sensitivity (Guru *et al.,* 2025; Pan *et al.,* 2021; Shimoda and Honda, 2013). Advances in LED technology enable spectral manipulation to target specific pest taxa while minimizing capture of non-target taxa. Previous studies have established foundational knowledge regarding species-specific spectral preferences, such as the visual orientation of thrips and hemipteran pests toward yellow and green wavelengths (Allan *et al.,* 2020; Liu *et al.,* 2022).

Furthermore, innovations in LED design have been explored for general IPM applications (Liu *et al.,* 2025). However, comprehensive field-based evaluations that simultaneously integrate spectral performance, ecological selectivity, and energy efficiency under the complex temporal dynamics of tropical agroecosystems remain critically limited (Adams *et al.,* 2025; Jones *et al.,* 2017).

The novelty of this study lies in its multidimensional quantitative approach. Unlike prior research that primarily focused on isolated metrics such as total abundance or physiological phototaxis, this study uniquely integrates species-specific capture rates with rigorous ecological safety indices (Target Selectivity Percentage and Target to Non-target Ratio) and a precise energy-based metric (Capture Efficiency Index) optimized specifically for key pests in tropical shallot cultivation. By addressing these combined parameters, this study aimed to evaluate the spectral effectiveness, species-specific attraction, ecological selectivity, and energy efficiency of LED traps, ultimately establishing a robust and sustainable framework for integrated pest management (IPM).

MATERIALS AND METHODS

Location

The study was conducted in a shallot field in Bone Regency, South Sulawesi Province, Indonesia, from April to July 2025.

Experimental design

Three LED spectral treatments were evaluated: White LED (380–700 nm), Yellow LED (570–590 nm), and Purple LED (380–750 nm). Each LED unit operated at 15 W for 12 hours nightly (18:00–06:00). Traps were positioned 30–40 cm above canopy level.

Insect sampling and identification

Captured arthropods were collected daily and identified morphologically. Insects were categorized as: (1) Target pests and (2) Non-target organisms (predators and pollinators).

Ecological selectivity metrics

Target Selectivity Percentage (TSP) was used to quantify the proportion of economically important pest species among the total captured insects: $TSP(\%)=(N_t/N)\times 100$, where N_t represents the total number of target pest individuals, and N represents the total number of captured insects across all treatments. Higher TSP values indicate greater trapping specificity toward pest taxa.

Target to Non-target Ratio (TNR) was calculated to express the relative capture intensity of pest insects compared with beneficial organisms: $TNR=N_t/N_{nt}$, where Nnt represents the number of non-target individuals. Higher TNR values indicate improved ecological selectivity.

The Ecological Safety Index (ESI) was calculated to assess the overall environmental compatibility of the trapping system: $ESI=1-(N_{nt}/N)$. ESI values range between 0 and 1, with values approaching 1 indicating minimal non-target impact and high ecological safety.

Energy efficiency metrics

The energy consumption of each LED trap was calculated based on rated power and operational duration. Each unit operated at 15 W for 12 hours per night, resulting in a daily energy consumption of 180 Wh. Total energy consumption during the experimental period was calculated as $E_{total} = P \times t \times d$, where P is lamp power (15 W), t is nightly operation time (12 h), and d represents the number of operational days.

The Capture Efficiency Index (CEI) was calculated to quantify the number of insects captured per unit of energy consumed: $CEI=N/E_{total}$, where N is the total number of insects captured, and Etotal is the total energy consumption (Wh).

Statistical analysis

Data were analyzed using one-way and two-way ANOVA followed by Tukey's HSD test at α = 0.05. Effect size (η^2) was calculated.

RESULTS

Total insect capture and spectral influence

One-way ANOVA indicated a highly significant effect of LED color on total insect capture (F = 38.39; $p < 0.001$). White LED recorded the highest mean capture (604.00 ± 139.31 individuals), significantly higher than yellow (53.00 ± 11.53) and purple LEDs (69.67 ± 59.08). Broad-spectrum white light stimulates multiple photoreceptors, including UV and blue-sensitive opsins in nocturnal insects (Ogawa *et al.,* 2015; McMahon *et al.,* 2022) (Table 1).

Table 1. Total insect capture under different LED spectra

LED color	Mean capture (Individuals)
White	604.00 ± 139.31^a
Yellow	53.00 ± 11.53^b
Purple	69.67 ± 59.08^b

Different letters indicate significant differences at $p < 0.05$ (Tukey HSD).

Species-specific spectral preference

One-way ANOVA confirmed that LED color significantly affected capture of *T. tabaci* (F(2,6) = 7.74; $p = 0.0218$; $\eta^2 = 0.72$) and *A. gossypii* (F(2,6) = 12.17; $p = 0.0077$; $\eta^2 = 0.80$). For *S. exigua*, purple LEDs recorded the highest mean capture (10.00), followed by white LEDs (9.00) and yellow LEDs (5.00). In contrast, *T. tabaci* showed a pronounced preference for yellow LEDs (mean = 15.00), compared with white (1.67) and purple (1.33). Similarly, *A. gossypii* capture was highest under yellow LEDs (mean = 3.33) (Table 2).

Table 2. Mean number of target pests captured by different LED spectra

LED color	Target pests captured		
	Spodoptera exigua	*Thrips tabaci*	*Aphis gossypii*
White	9.00 ± 7.00^a	1.67 ± 2.00^a	0.67 ± 0.58^a
Yellow	5.00 ± 2.00^a	15.00 ± 8.00^b	3.33 ± 1.15^b
Purple	10.00 ± 4.36^a	1.33 ± 1.15^b	0.33 ± 0.58^b

Different letters indicate significant differences at $p < 0.05$ (Tukey HSD).

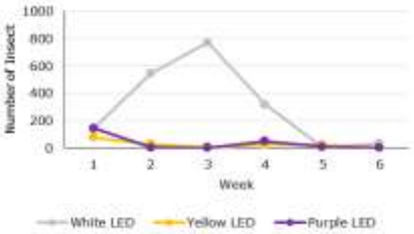

Fig. 1. Target pests captured by different LED spectra

Temporal dynamics

Two-way ANOVA indicated that both LED color (F = 16.89; $p < 0.001$) and observation week (F = 3.30; $p = 0.0148$) significantly influenced insect capture. Peak captures occurred during weeks 2–4, particularly under white LEDs, with week 3 showing the highest cumulative abundance (Fig. 1).

Table 3. Ecological selectivity indices of LED traps

LED Color	TSP (%)	TNR	ESI
White	1.88	0.019	0.018
Yellow	44.03	0.787	0.440
Purple	16.75	0.201	0.167

Table 4. Capture Efficiency Index (CEI) of LED traps

LED Color	CEI (Insects per Wh)
White	0.24
Yellow	0.02
Purple	0.03

Ecological selectivity and energy efficiency

Total target pest individuals across all treatments amounted to 130 individuals out of 2,180 total captured insects, resulting in a Target Selectivity Percentage (TSP) of 5.96% (Table 3). White LEDs generated the highest Capture Efficiency Index (CEI) in terms of insects per Wh. However, yellow LEDs exhibited greater efficiency when evaluated per target pest captured (Table 4).

DISCUSSION

Total insect capture and spectral influence

The present study demonstrated that LED color significantly influenced insect capture in shallot fields, both in terms of total abundance and species-specific responses. The significantly higher capture under white LED suggests that broad-spectrum light (380–700 nm) attracts a wider range of nocturnal and crepuscular insects (Charvalakis *et al.,* 2025; Baik *et al.,* 2026).

Species-specific spectral preference

The strong attraction to yellow wavelengths corresponds with documented peak visual sensitivity in hemipteran and thysanopteran pests, which rely on reflectance cues similar to young foliage (Allan *et al.,* 2020; Liu *et al.,* 2025). Yellow wavelengths (570–590 nm) closely resemble host-plant reflectance spectra, enhancing visual orientation behavior in phloem-feeding insects.

Temporal dynamics

The high variability observed in weekly captures likely reflects fluctuations in pest population dynamics influenced by environmental factors. In tropical agroecosystems, pest abundance often peaks during vegetative growth phases when foliage quality and nutrient availability are optimal (Kimondiu *et al.,* 2017; Abbas *et al.,* 2019).

Ecological selectivity and Energy efficiency

Ecological selectivity reflects the balance between pest suppression and biodiversity conservation. The extremely low selectivity of white LEDs suggests non-discriminatory phototactic stimulation across multiple insect taxa, potentially disrupting ecological balance (Parab *et al.,* 2021). Therefore, implementing wavelength-specific LED systems represents a mitigation strategy to reduce ecological disturbance (Gaston *et al.,* 2012; Marangoni *et al.,* 2022). From an IPM perspective, yellow LEDs, despite lower total capture, achieved substantially higher target-specific efficiency.

CONCLUSION

LED spectral composition significantly influences insect attraction in shallot agroecosystems. White LEDs maximize overall insect capture but lack selectivity. Yellow LEDs selectively attract key sucking pests, particularly *T. tabaci* and *A. gossypii*, while reducing non-target impacts. Although white LEDs show higher overall capture efficiency, yellow LEDs provide superior target-specific energy efficiency and ecological safety. Wavelength-specific LED traps therefore represent a sustainable component of integrated pest management in shallot cultivation.

RECOMMENDATION(S)

Wavelength-specific yellow LED traps should be integrated into IPM programs for shallot cultivation. Deployment is recommended during peak vegetative growth stages to maximize suppression of sucking pests while conserving beneficial insects. Future studies should evaluate long-term biodiversity impacts and optimize trap density under different agroecological conditions.

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