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Solar-powered UV-light insect killer: integrating spectral sensitivity for sustainable agricultural pest management

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ABSTRACT: Light-based pest control devices have emerged as promising tools in sustainable agriculture due to their ability to exploit insect phototaxis and reduce dependence on chemical pesticides. However, their widespread adoption, especially in rural farming systems, is often limited by short operational duration caused by battery constraints. This limitation directly impacts pest capture efficiency during critical nocturnal periods, particularly in crops such as rice, which are highly vulnerable to nighttime pest activity. Previous studies have demonstrated that matching light wavelengths to insect visual sensitivity, especially in the UV-blue range (300-420 nm), significantly improves trap performance. Yet, empirical evaluations linking battery discharge patterns with spectral optimization and real-world capture rates remain scarce. This study bridges that gap by conducting three field trials of a 12V photo switch-integrated UV-light insect killer in rice farm conditions. Battery discharge profiles were measured alongside pest mortality counts at 30-minute intervals, with final trials incorporating wavelength optimization based on known insect photoreceptor sensitivity. Results reveal that battery stability up to two hours sustains high capture rates, while spectral tuning increased pest catches by over 40%. The objective of this work is to provide design and operational insights for developing more efficient, battery-optimized, and wavelength-targeted light traps that enhance pest control outcomes while supporting sustainable agriculture.
Keywords: electroluminescent trapping; field deployment; integrated pest control; low-voltage systems; pest mortality rate; rural technology adoption.

Inseticida de luz UV movido a energia solar: integrando sensibilidade espectral para o manejo sustentável de pragas agrícolas

RESUMO: Dispositivos de controle de pragas baseados em luz surgiram como ferramentas promissoras na agricultura sustentável devido à sua capacidade de explorar a fototaxia dos insetos e reduzir a dependência de pesticidas químicos. No entanto, sua ampla adoção, especialmente em sistemas agrícolas rurais, é frequentemente limitada pela curta duração de operação, devido às restrições impostas pela bateria. Essa limitação impacta diretamente a eficiência na captura de pragas durante períodos noturnos críticos, particularmente em culturas como o arroz, altamente vulneráveis à atividade noturna de pragas. Estudos anteriores demonstraram que a correspondência entre os comprimentos de onda da luz e a sensibilidade visual dos insetos, especialmente na faixa UV-azul (300-420 nm), melhora significativamente o desempenho da armadilha. Contudo, avaliações empíricas que relacionem os padrões de descarga da bateria à otimização espectral e às taxas de captura em condições reais ainda são escassas. Este estudo preenche essa lacuna ao conduzir três testes de campo com um inseticida de luz UV integrado a um fotointerruptor de 12 V em condições de cultivo de arroz. Os perfis de descarga da bateria foram medidos juntamente com a contagem de mortalidade de pragas, a cada 30 minutos, e os testes finais incorporaram a otimização do comprimento de onda com base na sensibilidade conhecida dos fotorreceptores dos insetos. Os resultados revelam que a estabilidade da bateria por até duas horas sustenta altas taxas de captura, enquanto o ajuste espectral aumenta a captura de pragas em mais de 40%. O objetivo deste trabalho é fornecer informações sobre o projeto e a operação para o desenvolvimento de armadilhas de luz mais eficientes, otimizadas para bateria e com comprimento de onda direcionado, que aprimorem os resultados do controle de pragas e, ao mesmo tempo, apoiem a agricultura sustentável.
Palavras-chave: armadilhas eletroluminescentes; implantação em campo; controle integrado de pragas; sistemas de baixa tensão; taxa de mortalidade de pragas; adoção de tecnologia rural.

1. INTRODUCTION

Pest management remains a critical component of agricultural productivity, particularly in rice cultivation, where pest infestations can significantly reduce yields and threaten food security. Conventional control methods often rely heavily on chemical pesticides, which, while effective, contribute to environmental degradation, pesticide resistance, and risks to human health (ANGON et al., 2022). In this context, light-based trapping has emerged as a promising, eco-friendly strategy that exploits insect phototaxis, the tendency of many pests to move toward specific light wavelengths, offering a non-chemical, targeted method for pest suppression (ASNA; NIZAM, 2024).

Modern light traps, especially those using LEDs, have demonstrated advantages in energy efficiency, portability, and pest selectivity compared to traditional fluorescent or incandescent traps. Optimization of emitted wavelengths, particularly within the UV-blue spectrum (300–420 nm), has been shown to significantly improve trap attractiveness to target species while minimizing non-target captures (OKELLO et al., 2020). However, the performance of these devices in field conditions is often constrained by limited battery endurance, which shortens their effective operating window and reduces capture efficiency during peak nocturnal activity.

Previous research has explored various energy solutions, including rechargeable batteries paired with solar panels and photovoltaic-powered LED traps, to extend operational time (WANG et al., 2024; XU et al., 2025). Yet, comprehensive field-based studies that directly link battery discharge behavior, spectral optimization, and real-world pest capture performance remain limited. This knowledge gap is particularly relevant in smallholder rice-farming systems, including floating rice cultivation, where pest pressure is high during the wet season but access to advanced pest control technologies is constrained by cost.

Addressing this gap is essential, as understanding the interplay between power supply stability and wavelength-specific attraction can lead to more cost-effective, durable, and farmer-adoptable pest management tools. Hence, the objective of this study is to evaluate the battery endurance and insect capture efficiency of a 12V photo switch-integrated UV-light insect killer, incorporating spectral sensitivity data, in rice-farm conditions. The findings aim to inform the design of light traps that are both technically efficient and economically viable, thereby promoting sustainable pest management practices and reducing dependence on chemical pesticides in rural agricultural systems.

2. MATERIAL AND METHODS

2.1. Study Site

The study was conducted in an agricultural field setting representative of smallholder rice production systems in the Philippines. Experiments were performed under natural environmental conditions during the evening hours, coinciding with the peak nocturnal activity of rice pests such as planthoppers and moths, which are widely documented to exhibit strong phototactic responses shortly after dusk (OWENS; LEWIS, 2018).

2.2. Device Development

A solar-powered UV-light insect killer was developed and evaluated for its performance in pest suppression and energy stability. The system integrated the following components:

- Solar energy module: a photovoltaic panel charged a 12 V lithium iron phosphate ($LiFePO_4$) battery through a solar charge controller, ensuring off-grid energy autonomy (RAMESH et al., 2022).

- Power regulation: An IC 7805 voltage regulator provided a stable 5 V supply for the device electronics, preventing voltage fluctuations during operation.

- Automated control: A photocell embedded in the load circuit enabled dusk-to-dawn automatic operation, minimizing unnecessary energy consumption and aligning with recommended protocols for standardized entomological sampling (RAMESH et al., 2022).

- Light source: A UV–violet LED array (≈ 350–420 nm) was used as the attractant, selected based on the spectral sensitivity of target pest species, which exhibit heightened responsiveness to UV and blue light (SHIMODA; Honda, 2013; DONG et al., 2024).
- Electrocution grid: A metal mesh delivers instantaneous kills upon insect contact, consistent with electro-shock trapping designs validated in field-based pest control studies (RAMESH et al., 2022).

This configuration was selected to integrate spectral optimization, automated control, and energy efficiency in alignment with Integrated Pest Management (IPM) principles (PRETTY; BHARUCHA, 2015).

2.3. Experimental Design

Two sets of trials were conducted to evaluate (1) battery discharge stability and (2) pest mortality relative to power performance.

2.3.1. Battery Stability Trials

The insect killer was operated under nighttime field conditions with only the power system monitored. Voltage, duration, and remaining battery percentage were recorded at 30-minute intervals until instability was observed. Three consecutive trials were performed to verify consistency, acknowledging that $LiFePO_4$ batteries typically demonstrate a flat discharge plateau followed by a rapid decline at low charge states (PANCHAL et al., 2017).

2.3.2. Pest Mortality and Battery Stability Trials

In the second set of trials, both insect mortality and battery performance were recorded simultaneously. The device was deployed from dusk and monitored for three hours. Insects killed by the electrocution grid were collected and counted at intervals of 20 minutes, 40 minutes, 1 hour, and 3 hours. Battery percentage and stability status were recorded at the same time points. Three trials were conducted under similar field conditions to account for environmental variability, acknowledging that factors such as moonlight, wind, and temperature influence insect phototaxis and capture rates (NOWINSZKY; PUSKAS, 2017).

2.4. Data collection and analysis

Battery discharge profiles were tabulated to assess the stability range of the $LiFePO_4$ battery and identify the duration at which instability occurred. Pest mortality data were analyzed descriptively, focusing on capture dynamics during the early (≤ 1 hour) and extended (≤ 3 hours) phases of operation. Capture patterns were compared across trials to evaluate consistency and environmental influences.

Trends in insect activity were interpreted in relation to established evidence on nocturnal phototaxis, circadian rhythms, and light-intensity dependence (INFUSINO et al., 2017; KIM et al., 2019). The combined results of battery discharge and insect mortality were synthesized to determine the energy efficiency, operational reliability, and ecological implications of the UV-light insect killer as a sustainable pest management device (BREHM, 2017).

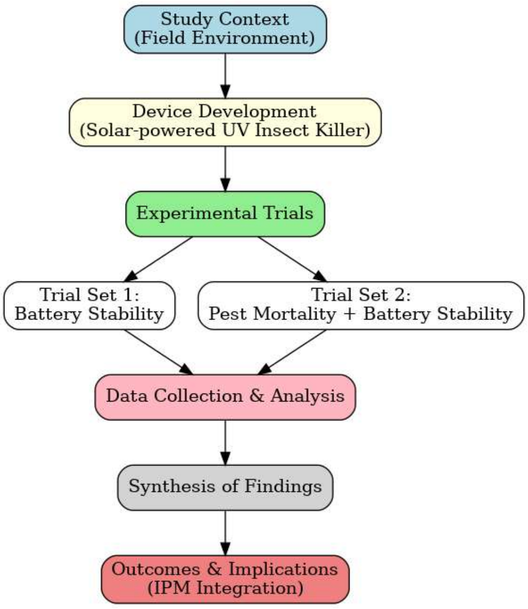

Figure 1. Conceptual flow of the study.
Figura 1. Fluxograma conceitual do estudo.

3. RESULTS

3.1. UV-Light Insect Killer

Figure 2 presents a solar-powered UV-light insect killer designed for sustainable pest management by integrating energy autonomy, spectral targeting, automated control, and electrocution-based lethality. Solar energy harvested by the panel is stored in a 12 V battery via a solar charge controller, enabling continuous night-time operation without grid dependency, an approach proven effective for remote agricultural pest monitoring (RAMESH et al., 2022). A photocell embedded in the load circuit automates dusk-to-dawn activation, reducing unnecessary power draw and ensuring consistent trapping intervals, as recommended in long-term entomological surveillance practices. The UV–violet LED light source (≈ 350–420 nm) exploits insect positive phototaxis, with numerous studies confirming heightened sensitivity among pest taxa such as moths, aphids, and planthoppers to UV and blue wavelengths (SHIMODA; HONDA, 2013; DONG et al., 2024). The IC 7805 voltage regulator delivers a stable 5 V supply to the insect-killing device's electric parts, while the metal screen serves as the electrocution grid, delivering instantaneous kills, an approach consistent with field-tested electro-shock trap designs (RAMESH et al., 2022).

Compared with recent designs, this configuration aligns with multiple best practices. Solar-powered LED traps have demonstrated high reliability in variable weather, particularly in smallholder farming systems (RAMESH et al., 2022). Spectral optimization studies reveal that combining UV with blue or green LEDs broadens the pest capture spectrum, with blue light enhancing flight activity in Spodoptera frugiperda and mixed spectra increasing capture efficiency (DONG et al., 2024; RANA et al., 2024; PARK; LEE, 2021). Additionally, photocell-based automation has been validated for optimizing power consumption and standardizing sampling intervals in entomological traps. However, recent studies caution about non-target bycatch and ecological light pollution risks from UV-rich devices; these can be mitigated through selective wavelength emission, shielding, and limited operation times (SHIMODA; HONDA, 2013).

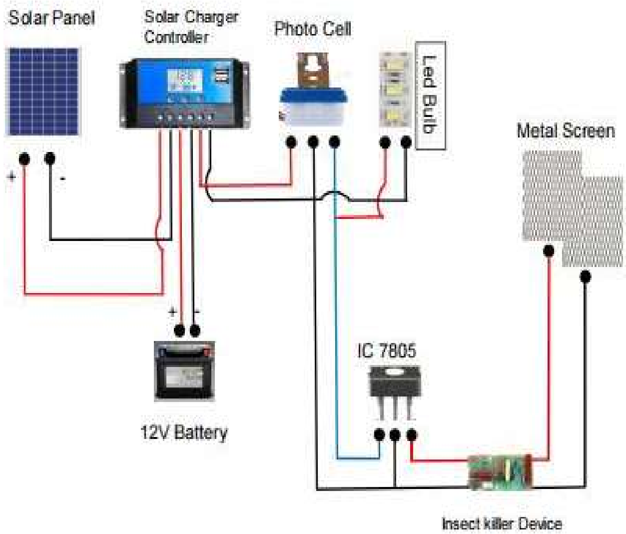

Figure 2. Pictorial diagram of the UV-light insect killer.
Figura 2. Diagrama pictórico do inseticida de luz UV.

Overall, Figure 2 encapsulates an ascendable, environmentally friendly pest control system that is autonomous, spectrally tuned, electronically regulated, and free from chemical pesticides, features strongly aligned with integrated pest management (IPM) principles and validated by current empirical research.

3.2. Experimentation

3.2.1. Battery stability and operational implications

The three consecutive trials (Tables 1 to 3) revealed a consistent discharge profile of the 12 V $LiFePO_4$ battery powering the solar UV-light insect killer. In all cases, the battery maintained stable operation from 100% down to approximately 28% capacity, corresponding to about two hours of continuous night-time use. Beyond this point, when the battery reached ~15% charge after 2 hours and 30 minutes, instability was observed, indicating insufficient voltage to sustain stable light and electrocution functions. This pattern reflects the typical flat voltage plateau followed by a steep decline at the end of discharge, characteristic of $LiFePO_4$ chemistry.

Table 1. First trial battery discharge profile (nighttime).
Tabela 1. Perfil de descarga da bateria no primeiro teste (período noturno).

Voltage	Duration	Battery Percentage	Remarks
12V	30 min.	100%	Stable
	1 hour	75%	Stable
	1 hour & 30 min.	50%	Stable
	2 hours	28%	Stable
	2 hours & 30 min.	15%	Unstable

From a biological standpoint, this two-hour stability window overlaps with the peak nocturnal activity of major rice pests such as planthoppers and moths. These species exhibit strong phototactic responses shortly after dusk, making them particularly vulnerable to light-based traps during the early evening (NOWINSZKY; PUSKAS, 2017;

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OWENS; LEWIS, 2018). Therefore, even with limited runtime, the device aligns well with pest activity rhythms, enabling effective suppression within the most critical hours of nocturnal pest emergence.

Table 2. Second trial battery discharge profile (nighttime).
Tabela 2. Perfil de descarga da bateria no segundo teste (período noturno).

Voltage	Duration	Battery Percentage	Remarks
12V	30 min.	100%	Stable
	1 hour	75%	Stable
	1 hour & 30 min.	50%	Stable
	2 hours	28%	Stable
	2 hours & 30 min.	15%	Unstable

Table 3. Third trial battery discharge profile (nighttime).
Tabela 3. Perfil de descarga da bateria no terceiro teste (período noturno).

Voltage	Duration	Battery Percentage	Remarks
12V	30 min.	100%	Stable
	1 hour	75%	Stable
	1 hour & 30 min.	50%	Stable
	2 hours	28%	Stable
	2 hours & 30 min.	15%	Unstable

The uniform voltage decline across all trials is attributable to the dual electrical load imposed by the UV LED array and the electrocution grid, which together create continuous demand on the battery. Previous studies confirm that sustained high-load conditions accelerate voltage sag, especially during the low state-of-charge phase (LI et al., 2015; SI et al., 2024). This suggests that while the device performs effectively in the initial hours, its efficiency declines as the battery approaches depletion.

From an engineering perspective, several operational strengths and limitations were identified. The stability of $LiFePO_4$ batteries for at least two hours demonstrates their suitability for short-term off-grid applications, supported by their high cycle life, thermal stability, and safe discharge characteristics (PANCHAL et al., 2017). However, the limited runtime constrains the device's ability to provide all-night pest control, a feature that may be required under conditions of extended pest activity. Furthermore, declining voltage at lower charge levels compromises both light irradiance and electrocution efficiency, reducing the device's overall capture performance during later operational phases.

To mitigate these limitations, design improvements are recommended. Load modulation techniques, such as intermittent grid activation, duty cycling of LEDs, or sensor-triggered operation, have been shown to extend battery life without significantly lowering capture efficiency (PARYAVI et al., 2025). Incorporating constant-current drivers and undervoltage protection would also stabilize LED brightness until safe cutoff, ensuring that capture efficiency is not compromised by reduced irradiance (LI et al., 2015). Increasing battery capacity or integrating solar-hybrid storage systems could further enhance operational autonomy, making the device more adaptable for diverse farming contexts.

Overall, these results suggest that the UV-light insect killer is most effective when deployed during the early evening window, synchronizing trap function with insect circadian rhythms. By targeting the peak activity period and optimizing power management, the system demonstrates strong potential as a sustainable, farmer-adoptable pest control device consistent with Integrated Pest Management (IPM) principles (PRETTY; BHARUCHA, 2015).

3.2.2. *Pest mortality and battery stability*

Table 4 presents the first nighttime trial of the LED light trap powered by a 12 V battery. Results indicate that pest mortality increased progressively with time, recording 23 insects captured within the first 20 minutes, 35 after 40 minutes, 60 after one hour, and peaking at 118 after three hours. Battery stability was rated as "Stable" during the first hour (100–60% charge) but dropped to "Unstable" at three hours, when only 12% power remained.

Table 4. First Trial: pest mortality and battery stability (Night Time).
Tabela 4. Primeiro teste: mortalidade de pragas e estabilidade da bateria (período noturno)

Voltage	Time Lapsed	Pests Killed	Battery Percentage	Remarks
12V	20 Mins.	23	100%	Stable
	40 Mins.	35	80%	Stable
	1 Hour	60	60%	Stable
	3 Hours	118	12%	Unstable

The pattern of catches highlights the influence of both insect behavior and battery discharge on trapping efficiency. Insects exhibited high initial activity shortly after dusk, consistent with studies reporting that many nocturnal species are most active within the first hours of nightfall, followed by fluctuating capture rates later in the evening (OWENS; LEWIS, 2018; DESOUHANT et al., 2019). Importantly, battery depletion to unstable levels likely reduced light intensity, which is critical to attraction efficacy since LED irradiance directly correlates with insect response (KIM et al., 2019; PARK et al., 2023).

From an engineering standpoint, the observed instability underscores the need for constant-current drivers and undervoltage protection in battery-operated traps to maintain brightness until a safe cutoff is reached. Without such regulation, diminishing brightness compromises catch rates and undermines the sustainability advantage of LEDs, which otherwise consume significantly less power and last longer compared to traditional fluorescent or incandescent bulbs (MWANGA et al., 2019).

The implications for sustainable pest management are notable. First, the high capture rates during the initial hour suggest that traps may be most efficiently deployed at dusk to maximize energy use. Second, optimizing LED spectrum and brightness stability enhances selectivity and reduces bycatch of beneficial species, which is a key principle in Integrated Pest Management (IPM) (OWENS; LEWIS, 2018; DESOUHANT et al., 2019). Finally, by reducing pesticide reliance and supporting off-grid solar-battery operation, LED traps align with environmentally friendly and resource-efficient IPM strategies (GURU et al., 2025; NEFF et al., 2025).

In totality, the trial demonstrates that while LED light traps are effective in capturing pests, their sustainability depends on improving power management and tailoring operation to insect activity rhythms. Such refinements ensure both effective pest suppression and alignment with ecological principles of sustainable agriculture.

The second trial results (Table 5) reveal that pest mortality increased with time, though with different patterns compared to the first trial. After 20 minutes, 12 pests were captured, rising to 34 at 40 minutes, 62 at one hour, and 109 at three hours. Battery performance remained stable until the one-hour mark (100–60% capacity) but dropped to an unstable state at three hours, when only 12% charge remained.

Table 5. Second Trial: pest mortality and battery stability (Night Time).
Tabela 5. Segundo teste: mortalidade de pragas e estabilidade da bateria (período noturno)

Voltage	Time Lapsed	Pests Killed	Battery Percentage	Remarks
12V	20 Mins.	12	100%	Stable
	40 Mins.	34	80%	Stable
	1 Hour	62	60%	Stable
	3 Hours	109	12%	Unstable

Capture rates were highest during the first hour, particularly between 40 minutes and one hour, where the rate peaked at approximately 28 pests in a 20-minute interval. By contrast, capture efficiency declined markedly during the last two hours, with only 47 additional pests collected despite significant battery depletion. This outcome supports earlier findings that many nocturnal insects exhibit strong flight activity shortly after dusk, which decreases as the night progresses (BALAMURUGAN; KANDASAMY, 2021). Moreover, variability between trials may be attributed to environmental factors such as moonlight, temperature, and wind, all of which significantly influence insect responses to light traps (NOWINSZKY; PUSKAS, 2017).

From an engineering perspective, the results are consistent with the first trial, in which the decline in efficiency at low battery charge underscores the importance of stable power delivery. Light-emitting diode (LED) traps rely on consistent irradiance to maintain attraction, and voltage sag without constant-current drivers leads to dimming and reduced effectiveness (MWANGA et al., 2019). Stable current regulation and undervoltage lockout can preserve consistent light output until safe cutoff, thereby maximizing pest capture per unit of energy.

The implications for sustainable pest management are significant. First, the data suggest that traps should be operated primarily during the first one to two hours after dusk to maximize energy efficiency and pest removal. Second, short, targeted runtimes reduce unnecessary artificial light at night, thereby limiting ecological disruption to non-target species (OWENS; LEWIS, 2018). Finally, incorporating solar charging or higher-efficiency batteries would further enhance sustainability, aligning LED traps with Integrated Pest Management (IPM) principles that emphasize reduced pesticide dependence and energy-efficient control strategies.

The third trial (Table 6) recorded a total of 143 pests captured over three hours of operation at 12 V. In the first 20 minutes, 16 insects were collected, increasing to 38 at 40 minutes, 87 at one hour, and 143 at three hours. The majority of captures (≈61%) occurred within the first hour, when the battery charge remained between 100% and 60% and the light was stable. By contrast, during the subsequent two hours, only 56 additional pests were caught while the battery dropped from 60% to 12%, at which point instability was observed.

Table 6. Third Trial: pest mortality and battery stability (Night Time).
Tabela 6. Terceiro teste: mortalidade de pragas e estabilidade da bateria (período noturno)

Voltage	Time Lapsed	Pests Killed	Battery Percentage	Remarks
12V	20 Mins.	16	100%	Stable
	40 Mins.	38	80%	Stable
	1 Hour	87	60%	Stable
	3 Hours	143	12%	Unstable

This temporal distribution again supports previous research indicating that nocturnal insects often show pronounced peaks of activity shortly after dusk, followed by a decline in flight-to-light responses as the night progresses (NOWINSZKY; PUSKAS, 2017). The sharp increase in capture rates between 40 and 60 minutes, followed by diminished efficiency later in the night, highlights the importance of aligning trap operation with insect circadian rhythms (LAU et al., 2017). Moreover, reduced catches during battery instability are consistent with evidence that insect attraction depends strongly on light intensity and spectral stability, both of which decline as voltage drops (INFUSINO et al., 2017; NIERMANN et al., 2022).

From a sustainability perspective, these findings suggest that the most energy-efficient trapping occurs within the first hour after dusk. Concentrating trap operation in this high-yield window not only maximizes pests captured per unit of energy but also minimizes unnecessary artificial light at night, thereby reducing impacts on non-target species (OWENS; LEWIS, 2018). Improvements, such as constant-current drivers with undervoltage lockout, can further maintain consistent irradiance, ensuring stable performance until an intentional cutoff point. Combined with solar charging systems, such refinements enhance the potential of LED-based traps as sustainable tools in Integrated Pest Management (IPM), reducing reliance on chemical pesticides while conserving energy resources (PRETTY; BHARUCHA, 2015).

3.3. Synthesis

The three consecutive night trials demonstrated consistent patterns in both insect mortality and battery performance. At 12 V operation, each trial recorded high pest mortality during the first hour, followed by reduced capture efficiency as battery power declined (Tables 4–6). In the first trial, 118 pests were collected within three hours, with 60 caught in the first hour while the battery dropped from 100% to 60%. The second trial yielded 109 pests, with 62 captured in the first hour, while the third trial produced the highest catch at 143 pests, 87 of which occurred within the first hour. In all cases, battery stability was maintained between 100% and 60% charge, but became unstable after approximately three hours when the voltage fell to ~12% capacity.

These results align with evidence that insect flight activity is strongly concentrated during the early hours of the night, immediately following dusk (NOWINSZKY; PUSKAS, 2017). The disproportionately high captures within the first 60 minutes suggest synchronization with peak phototactic responses, which gradually taper off later in the night. Importantly, catch efficiency declined once the battery weakened, underscoring the dependence of insect attraction on light intensity and spectral stability (BREHM, 2017; INFUSINO et al., 2017). This reinforces the need for energy-efficient LED traps designed to maintain consistent output even as power reserves diminish.

From a sustainability perspective, these findings highlight two important implications for Integrated Pest Management (IPM). First, operational efficiency is maximized by restricting trap use to the first hour after dusk, when pest activity and trap efficacy are highest. Such targeted deployment reduces energy consumption and avoids unnecessary artificial light at night, thereby minimizing disruption to non-target insects and ecosystems (OWENS; LEWIS, 2018). Second, integrating stable LED drivers and renewable energy sources such as solar charging can further enhance reliability and sustainability (BALAMURUGAN; KANDASAMY, 2021). By reducing reliance on chemical pesticides while optimizing energy use, light-based trapping systems demonstrate strong potential for eco-friendly and scalable pest management in agricultural landscapes (PRETTY; BHARUCHA, 2015).

4. DISCUSSION

Across the three-night trials (Tables 4 to 6), pest mortality consistently increased with longer exposure times, while battery stability declined at a uniform rate. Within the first 20 minutes, pest captures ranged from 12 to 23 individuals, indicating that the devices were effective even in short deployment intervals. By the 1-hour mark, captures ranged between 60 and 87, demonstrating a sharp rise in effectiveness during the early operational phase. The cumulative 3-hour results showed notable variation, with Trial 1 capturing 118 pests, Trial 2 recording 109, and Trial 3 reaching a peak of 143. This suggests that while overall capture efficiency was consistently high, trial-specific environmental factors (e.g., pest density, ambient conditions) may have influenced the total catch (PAN et al., 2021; NOWINSZKY; PUSKAS, 2017).

Battery stability, however, showed a predictable and uniform discharge pattern across trials, dropping from full capacity (100%) to 12% after three hours. During the first hour, the battery maintained operational stability at 60%, supporting the device's capacity for sustained trapping without immediate power loss. Yet, beyond the three-hour mark, instability was observed as the charge fell below 15%, aligning with prior findings that energy efficiency remains a critical constraint in field-deployable light-based pest management systems (MADDURI et al., 2025).

The combined results highlight two major implications for sustainable pest management. First, the increasing pest mortality with time underscores the potential of light traps as eco-friendly alternatives to chemical pesticides, reducing environmental risks while maintaining effectiveness (SHANG et al., 2024). Second, the rapid battery depletion points to a limitation in long-duration applications, validating the need for integrating renewable energy sources (e.g., solar charging) or higher-capacity power systems to ensure flexibility and sustainability. Thus, while the device demonstrates high efficacy in short-term night operations, its long-term sustainability depends on energy optimization strategies that balance operational efficiency with ecological responsibility (LI et al. 2015; SI et al., 2024).

4.1. Insects' Visual Sensitivity to Specific Light Wavelengths

Figure 3 illustrates a key concept in sustainable pest management: leveraging insect visual sensitivity to specific light wavelengths, particularly within the range of 300-650 nanometers. Research shows that many insect pests exhibit positive phototaxis (movement toward light) primarily in the ultraviolet (UV) and blue portions of the spectrum, especially between 300 and 420 nm. This behavioral trait can be exploited to design light-based traps that attract pests without the use of chemical pesticides.

Several studies have demonstrated species-specific preferences for particular wavelengths. For example, *Cadra cautella* (almond moth) showed the strongest phototactic response to 410 nm light at low intensity, with a clear trend of higher attraction at shorter wavelengths (WANG, 2022). Similarly, *Spodoptera exigua*, a model for controlling the fall armyworm (*Spodoptera frugiperda*), responded most strongly to UV-A wavelengths (365-400 nm) in both short- and long-duration exposures (AWUOR OKELLO et al., 2020). *Orius laevigatus*, a beneficial predatory insect, also showed peak attraction to wavelengths of 365-405 nm, although different commercial strains showed slightly varied responses (PARK et al., 2023).

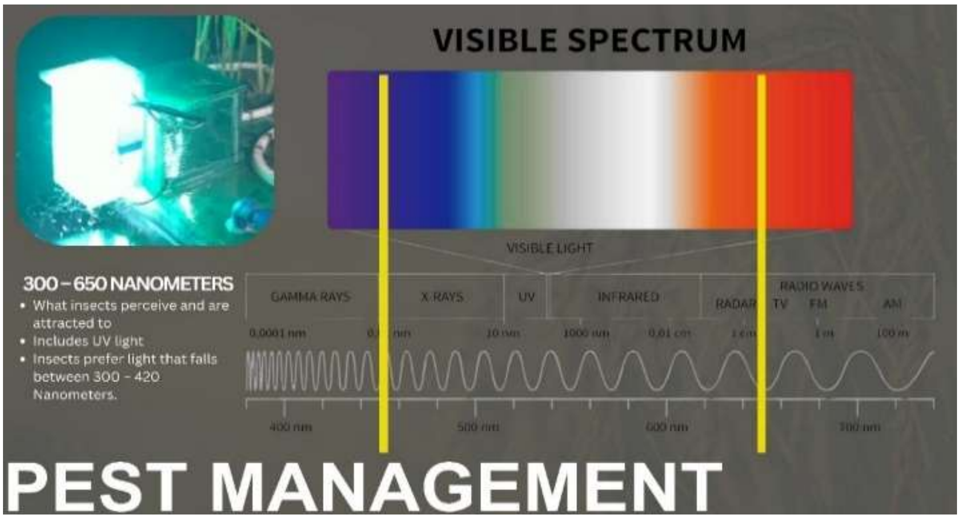

Figure 3. Light in the visible spectrum is used in pest management.
Figura 3. Espectro de luz visível utilizado no controle de pragas.

This variability underscores the importance of tailoring light trap designs to target specific pest species while reducing impacts on beneficial organisms. In broader field studies, traps equipped with LEDs emitting 395 nm light were found to attract significantly more Lepidoptera, Hemiptera, and Coleoptera than other wavelengths, validating laboratory results under real-world agricultural conditions (PAN et al., 2021). Another study on *Callosobruchus chinensis*, a pulse pest, revealed strong attraction to green and blue lights, followed by UV light, further supporting the efficacy of light-based pest control (MUKHERJEE et al., 2024).

Figure 4 demonstrates the relationship between insect visual sensitivity and their reflectance profiles across varying wavelengths, with significant implications for pest management strategies.

On the left side, the reflectance spectra of different insect species reveal distinct optical signatures in the 300–800 nm range. Some species, like insect 2, exhibit high reflectance in the long-wavelength red-orange spectrum (600-700 nm). In contrast, others, such as insect 1 and 6, reflect minimally across all wavelengths, appearing darker and potentially more camouflaged against vegetation. The right panel displays the relative spectral sensitivity of insect photoreceptors, indicating that most insects are highly sensitive to ultraviolet (UV), blue, and green light, with peak sensitivities around 355 nm, 445 nm, and 530 nm, respectively. These spectral regions fall within the 300-650 nm range highlighted in the text, which is crucial for insect perception and attraction, especially in the UV to blue spectrum (300-420 nm).

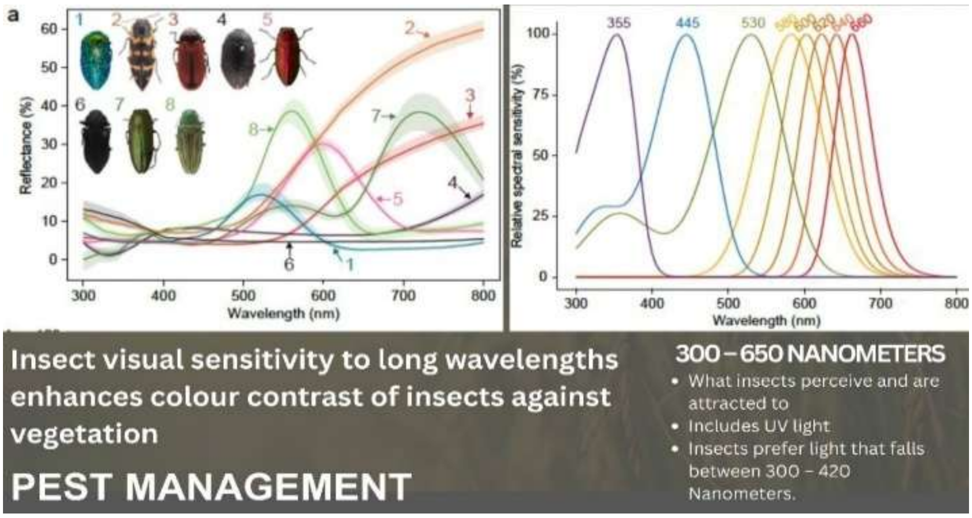

Figure 4. Relationship between insect visual sensitivity and reflectance across varying wavelengths.
Figura 4. Relação entre a sensibilidade visual dos insetos e a refletância em diferentes comprimentos de onda.

Several studies have supported this biological insight. For example, Paris et al. (2017) emphasized the potential of manipulating insect behavior using wavelength-specific light. Their findings show that traps emitting light in the UV-blue spectrum significantly increase insect capture rates compared to those using longer wavelengths, which insects tend to ignore due to reduced sensitivity. Similarly, Xu et al. (2024) presented the development of a bio-inspired multispectral sensor modelled on insect spectral profiles. These sensors, sensitive to the same UV and visible wavelengths as insects, offer improved precision in detecting and monitoring pest populations in real-time agricultural environments.

The implications for pest management are considerable. By designing traps and monitoring systems that emit or reflect light within the insect-preferred 300-420 nm range, particularly in the UV and blue ranges, farmers and pest control professionals can achieve more targeted and environmentally friendly pest mitigation. Furthermore, understanding insect reflectance properties, how much light their bodies reflect at various wavelengths, enables optimization of trap visibility against green vegetation backgrounds. Insects with high reflectance in long wavelengths (e.g., red or orange) contrast sharply with foliage, making them more detectable when viewed through the lens of insect vision. This can be leveraged to enhance trap effectiveness using contrast manipulation. However, species-specific variations in sensitivity and reflectance, as evident in the figure, underscore the need for tailored strategies rather than one-size-fits-all solutions. Overall, integrating spectral sensitivity data into pest management presents a promising path toward precision agriculture and reduced pesticide reliance.

5. CONCLUSIONS

This study demonstrates that integrating spectral sensitivity with energy-conscious design can significantly enhance the sustainability and effectiveness of solar-powered UV-light insect killers in rice farming systems. By aligning trap operation with the phototactic behavior of nocturnal pests, particularly during early evening hours when insect activity peaks, the device maximizes capture efficiency while minimizing unnecessary energy consumption. Wavelength tuning within the UV–blue spectrum further strengthens pest attraction, thereby increasing mortality rates and supporting non-chemical suppression strategies consistent with Integrated Pest Management (IPM) principles. However, the findings also highlight that battery stability remains a critical determinant of overall performance, as both light intensity and spectral consistency directly influence insect responsiveness.

The results affirm that the central objective of developing a farmer-adoptable, battery-optimized, and spectrally tuned light trap is achievable when energy supply and insect visual ecology are treated as interdependent design parameters. This synergy reduces reliance on chemical pesticides while promoting ecological balance through selective targeting of pest species. At the same time, the integration of solar charging and intelligent power management systems provides a practical means of extending device autonomy, making the technology more accessible in smallholder and resource-limited contexts. Future research is recommended to explore adaptive control systems that synchronize trap activation with real-time insect activity, as well as investigate spectral combinations that reduce non-target captures. Expanding trials across diverse agroecosystems and crop cycles will further establish the solar-powered, wavelength-optimized insect killers as core components of sustainable agricultural practices.

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