Uttar Pradesh Journal of Zoology

Volume 46, Issue 2, Page 87-94, 2025; Article no. UPJOZ.4510
ISSN: 0256-971X (P)

Integrating Artificial Intelligence with Insect Phototaxis: Transformative Innovations in Pest Control

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.56557/upjoz/2025/v46i24765

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://prh.mbimph.com/review-history/4510

Original Research Article

Received: 10/11/2024
Accepted: 13/01/2025
Published: 20/01/2025

ABSTRACT

Phototaxis or the responsiveness of insects with light stimuli represents an important mechanistic basis upon which pest management methods are approached. Traditional use of phototaxis-based technologies frequently employs merely a light trap for inducing the changing behavioral patterns observed among insects in pest management and the like. A great deal can change with novel approaches such as the application of AI. This paper explores the biological underpinnings of phototaxis, examines both conventional and modern applications of light-based pest control, and introduces the integration of AI to enhance precision and effectiveness. Recent breakthroughs, such as the use of tailored wavelengths of light to target specific insect species, are discussed in detail alongside emerging applications like smart farming systems that employ AI-driven decision-making. Energy efficiency, cost, and environmental impacts are all part of the discussion, making clear that sustainability needs to be found. Furthermore, the research will discuss future research

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***Cite as:** Mahato, Nityanando, Sayon Dey, Gourab Chakraborty, and Shouvik Debnath. 2025. "Integrating Artificial Intelligence With Insect Phototaxis: Transformative Innovations in Pest Control". UTTAR PRADESH JOURNAL OF ZOOLOGY 46 (2):87-94. https://doi.org/10.56557/upjoz/2025/v46i24765.*

directions in areas such as adaptive light-based traps, real-time monitoring, and AI-based predictive models that may respond dynamically to changing pest behavior and environmental conditions. By fusing insights derived from biological findings with state-of-the-art AI technologies, this paper looks forward to the prospect of presenting revolutionary phototaxis-driven strategies in pest management. The aim is to highlight how these integrated approaches might result in more environmentally friendly, highly efficient, and species-specific pest control methods that align with the principles of sustainable agriculture. Seen through this interdisciplinary lens, this paper contributes to the growing discourse about merging biological knowledge with technological innovation for global agricultural challenges.

Keywords: Phototaxis; pest management; Artificial Intelligence; light-based control; smart farming; sustainable agriculture; environmental impact.

1. INTRODUCTION

Traditionally, pest control relies on chemical, biological, and mechanical methods. Of these, light-based strategies have shown much promise because they target their application and have lower impacts on the environment. Phototaxis is a biologically ingrained behavior whereby insects are attracted or repelled to specific wavelengths of light. Recent advances in AI present opportunities to optimize such strategies to allow for real-time monitoring, species-specific targeting, and integration with other techniques of pest management. This paper explores the scientific basis of insect phototaxis, traditional approaches, and innovations in AI. Insect phototaxis" refers to how insects react behaviorally to light, whether moving towards it (positive phototaxis) or away from it (negative phototaxis) (Boerjan & Strauss, 2024). This phenomenon is only one of several behaviors of insects where foraging, mating, dispersal, and shelter-seeking occur. While different between insect groups, phototaxis is often species-specific and varies with ambient factors, life stages, and light stimuli. For example, some insects are active light avoiders to seek shelter or refuge while nocturnal moths exhibit positive phototaxis to artificial light sources at night (Kim et al., 2019). For a long time, entomologists and scholars have been fascinated by the phenomenon of insect phototaxis, primarily due to its potential applications in pest control. Due to their damaging capacity on agricultural crops, disease transmission, and upsets of ecosystem balance, pest insects persist as an issue in both agriculture and public health arenas (Yao et al., 2023). Traditionally, a variety of techniques have usually been employed to control the pest populations with chemical pesticides, which have, many times brought unintended adverse impacts to the environment with effects such as injury to non-target species, resistance in populations of pests, and contamination in ecosystems. Consequently, there is a growing demand for environmentally friendly, sustainable ways of controlling insect populations (Dey et al., 2025). One promising approach using the concepts of insect phototaxis to control and reduce pest populations is one of these approaches (Park & Lee, 2017). Apart from its biological significance, insect phototaxis is significant because it is a useful tool that may be used to control pests in various habitats. Light traps have been historically used to attract and capture pests such as flies, beetles, and moths (Ramesha et al., 2024). These light-based management methods are chemical-free and are therefore extremely desirable in situations where minimum chemical residues and protection of the environment are paramount. In agriculture, light traps are used to monitor insect populations so farmers can detect infestations early on and act quickly (Sun et al., 2014; Murchie et al., 2023). Such traps are commonly employed in urban areas to control mosquitoes, which reduces the demand for pharmaceutical insecticides. Phototaxis-based pest control has been revolutionized by technological advancements, particularly in the field of light-emitting diode (LED) technology. Due to its longer lifespan, energy efficiency, and ability to tailor specific wavelengths to target specific bug species, LED-based traps are now preferred over traditional incandescent lights. According to research, some nuisance insects are more attracted to specific light wavelengths, especially ultraviolet (UV), blue, and green light. This enables more accurate targeting and reduces non-target Effects (Yamaguchi & Heisenberg, 2011) (Qihang et al., 2017) (Donners et al., 2018) (Khan et al., 2021). For example, blue and green lights have been shown to attract flies and beetles, while UV light is very effective at attracting nocturnal insects such as moths. Significant advantages are realized from this wavelength selectivity, which reduces the capture of beneficial insects such as pollinators, which are crucial to agricultural ecosystems. There has also been an increase in the use of phototaxis-based pest management in combination with other sustainable agriculture methods including biological control and integrated pest management (IPM). Light-based traps can be used in combination with parasitoids, microbiological agents, or natural predators to efficiently control pest populations while reducing the usage of toxic pesticides (Kilis at al., 2022). Furthermore, solar-powered light traps are becoming a more affordable and environmentally friendly choice, particularly in isolated or resource-poor locations with limited access to energy (Cagliari et al., 2019). These traps lower operating costs and carbon footprints by using solar energy during the day to power light attractants at night. The use of phototaxis in pest management is not without its difficulties, despite its potential (Lin et al., 2024). One major concern is the interference caused by light pollution on non-target creatures and their natural behaviors. Environmental factors like ambient light, weather, and competing light sources affect the efficacy of phototaxis-based traps and generally reduce their efficiency in field settings. Insect phototaxis is well-established behavior that can be used practically for pest control applications. Overuse of artificial lighting in agricultural areas might interfere with nocturnal wildlife, such as pollinators and predators and other beneficial insects (Cagliari et al., 2019). New development, especially on solar power systems and LED technology, offers encouraging prospects to develop more economic, targeted, and environmentally friendly solutions for pest control. Utilizing these developments and combining phototaxis-based technologies with other environmentally acceptable methods will help to reduce our dependence on chemical pesticides and create a more sustainable agricultural future. Discussion of these developments will be provided in this review, which will also highlight the advantages and disadvantages of phototaxis in contemporary pest control techniques.

2. PHOTOTAXIS MECHANISMS IN INSECTS

2.1 The Mechanism of Light Detection

An insect senses light with a compound eye made of a multitude of ommatidia. With photoreceptors responsive to different wavelengths, ommatidium within each insect ommatidium allow it to detect many stimuli for the environment. Therefore, it relies on the light sensitivity of these photoreceptors in order to find food or mates and to discern days and nights.

Table 1. Integrated pest management strategies using phototaxis

Strategy	Description	Benefits
Targeted Pest Removal	Employing species-specific light traps to capture harmful pests while minimizing non-target effects.	Reduces pest populations with minimal environmental impact and preserves beneficial insect species.
Combination with Pheromone Traps	Integrating light traps with chemical attractants like pheromones for enhanced specificity and efficiency in pest capture.	Increases trap efficacy by combining sensory stimuli, thereby improving species targeting and reducing chemical usage.
Solar-Powered Light Traps	Deploying sustainable light traps powered by solar energy, particularly in remote or off-grid agricultural areas.	Promotes energy efficiency, lowers operational costs, and provides eco-friendly pest control solutions.
AI-Driven Smart Traps	Using smart traps integrated with AI and IoT for species identification, behavior analysis, and adaptive pest control strategies.	Enables automation, precision targeting, and adaptive responses, while providing valuable data for long-term management.
Circadian Rhythm Exploitation	Aligning light trap operation with the circadian activity patterns of pests to maximize capture during peak activity times.	Optimizes trap efficiency and minimizes wasted energy by targeting pests when they are most active.
Integration with Habitat Control	Strategically placing light traps in areas modified to enhance their effectiveness, such as near vegetation barriers or breeding	Combines mechanical control with habitat management for a holistic and sustainable approach.

Strategy	Description	Benefits
	sites.	
Supplementation with Biological Agents	Attracting pests to areas where natural predators or parasitoids are introduced, leveraging phototaxis for biological control.	Enhances the efficacy of biological control agents by concentrating pest populations in specific areas.
Tailored Light Wavelengths	Designing light traps with wavelengths optimized for specific pest species based on their phototactic preferences.	Reduces non-target effects, improves capture rates, and minimizes the environmental impact of light-based strategies
Phototaxis-Based Monitoring		Enables real-time pest population tracking, helps in early detection, and facilitates informed decision-making.

Table 2. Comparison of light wavelengths and insect attraction

Light Wavelength (nm)	Attractiveness of insects	Common Target species
280-320 nm	High	High sensitivity (Moths, mosquitoes)
320-400 nm	Moderate	Moderate sensitivity (Beetles, some flies)
400-500 nm	High	High sensitivity (Moths, certain flies)
500-600 nm	Low	Low sensitivity (Most beneficial insects, e.g., bees)
600-700 nm	Very Low	Very low sensitivity (Predatory insects)

Fig. 1. Sensitivity of insect eyes to specific wavelengths

2.2 Neural and Behavioural Responses

The ability of an organism to exhibit phototaxis requires neural circuits linking light detection to behavioral responses. Decoded in the optic lobe, photoreceptor signals are received by motor neurones to produce movement toward or away from light sources. The majority of flying insects have positive phototaxis. Some species, such as cockroaches, have demonstrated negative phototaxis.

2.3 Circadian Rhythms and Phototaxis

Phototactic behavior is highly controlled by circadian cycles that are internally controlled by biological clocks. While diurnal insects respond to light traps during the day, nocturnal insects such as moths have a greater response at night. The treatment of pests can be maximally timed with this knowledge.

2.4 Impact on the Environment due to Phototaxis

From Table 1. Other environmental factors affecting phototactic reactions include light intensity, humidity, and temperature. For example, the appealing potential of UV light will be affected by different environmental variables, hence each situation requires customized pest management strategies.

3. TRADITIONAL USES OF PHOTOTAXIS IN PEST CONTROL

3.1 Light Traps

Among the first applications of phototaxis in pest control is light traps. They were invented to attract and trap insects by using certain wavelengths of light to target pests, including moths, beetles, and flies. Light traps are very commonly used in agricultural and domestic applications.

3.2 UV lamps in fly control

UV lamps are very effective in controlling flies in urban and industrial areas. They work by the strong attraction of flies towards UV light, which often accompanies electrified grids or adhesive surfaces for capture and killing.4. Recent Innovations in Phototaxis-Based Pest Management.

4. RECENT INNOVATION IN PHOTO TAXIS-BASED PEST MANAGEMENT

LED-Based Light Traps full-scale change in the light traps began with the introduction of LED technology. LEDs are not only longer-lived and have less energy but also appear in a wider range of wavelengths. This property makes LEDs excellent for species-specific pest control.

4.1 Solar-Powered Light Traps

AI-Integrated Smart Traps.

IoT-enabled AI smart traps allow real-time monitoring and analysis of data. With the help of behavioural patterns, AI algorithms are capable of identifying the species trapped, calculating population densities, and helping optimize trapping tactics.

4.2 Smart Traps with AI Integration

AI-Integrated Smart Traps: IoT-enabled AI smart traps make real-time data monitoring and analysis possible. AI systems can calculate population densities, identify the species caught, and help in the optimization of trapping strategies by using behavioral patterns.

Adaptive Light-Based Traps: Developing systems that dynamically adjust light wavelengths based on real-time pest behavior and environmental conditions.

- Enhanced AI Models: Leveraging machine learning and neural networks for species-specific pest predictions and behavior analysis.
- Hybrid Pest Management Approaches: Combining phototaxis-based traps with biological and chemical control methods for a more comprehensive solution.
- Sustainable Designs: Innovating eco-friendly and energy-efficient pest control systems, such as advanced solar-powered traps.

From Table 2 - Comparison of Light Wavelengths and Insect Attraction:

This table compares various light wavelengths (280-700 nm) and their effectiveness in attracting insects. It highlights specific target species like moths, mosquitoes, and beetles, emphasizing wavelength sensitivity for optimizing pest control.

From Table 3 - Challenges in Phototaxis-Based Pest Control:

This table outlines challenges such as non-target effects, variability in insect responses, and light pollution. It suggests potential solutions like selective light traps, species-specific attraction research, and directional lighting.

From Table 4 - Advantages and Disadvantages of Phototaxis-Based Pest Control Methods:

This table evaluates methods like light traps, UV lamps, LED traps, solar-powered traps, and chemical attractants, highlighting their benefits (e.g., energy efficiency, disease vector reduction) and limitations (e.g., high initial cost, chemical resistance).

Table 3. Challenges in phototaxis-based pest control

Challenge	Description	Potential Solution
Non-Target Effects	Attraction of beneficial insects	Develop selective light traps
Variability in Response	Different pest species exhibit varying responses	Research species-specific attraction mechanisms
Light Pollution Concerns	Negative impact on nocturnal wildlife and ecosystems	Use directional lighting to minimize dispersal

Table 4. Advantages and disadvantages of phototaxis-based pest control methods

Method	Advantages	Disadvantages
Light Traps	Effective for monitoring pest populations	Can attract non-target species
UV Lamps	Reduces disease vectors	Limited range of effectiveness
LED Traps	Energy-efficient and programmable	Initial setup cost may be high
Solar-powered Traps	Sustainable and cost effective in remote areas	Dependence on sunlight for operation
Chemical attractants	Increases specificity in trapping	Potential chemical resistance in pests

Table 5. Integrated pest management strategies using phototaxis

Strategy	Description	Benefits
Biological Control	Combining light traps with natural predators	Enhances overall pest suppression
Chemical Attractants	Using pheromones alongside light traps	Improves targeting and reduces non- target catches
Habitat Management	Modifying the environment to limit pest access	Sustainable and eco-friendly approach
Smart Farming Integration	Using IoT sensors with light traps	Enhances real-time pest management capabilities

From Table 5 - Integrated Pest Management Strategies Using Phototaxis:

This table details strategies such as combining light traps with biological control, chemical attractants, habitat management, and smart farming integration. It emphasizes enhanced pest suppression, eco-friendly approaches, and real-time management capabilities.

5. INTEGRATION OF PHOTOTAXIS WITH OTHER PEST MANAGEMENT STRATEGIES

5.1 Phototaxis and Biological Control

The incorporation of phototaxis with biological control improves the management of pests. For instance, by using light traps, it is possible to lure pests into regions where biological predators or parasites have been released.

5.2 Phototaxis and Chemical Attractants

Combining phototaxis with chemical attractants, like pheromones, increases the trap's specificity and effectiveness. It makes pest capture more targeted and minimizes the adverse effects on non-target organisms.

5.3 Habitat Management and Phototaxis

On the level of management practice, phototaxis traps can be put together to form a plant-based barrier and crop rotation may be used in order to facilitate an effective pest management.

6. CHALLENGES AND LIMITATIONS

6.1 Side Effects Unintended

Light traps can cause disturbance to communities by attracting non-target species, for example beneficial insects. Improvements in AI and the ability to tailor wavelengths can reduce such impacts.

6.2 Individual and Interspecific Differences in Phototaxis Behaviour

Generalization of control methods for pests is prevented by phototactic response differences within species and between species. AI powered data analysis can help to identify and adapt to such differences

6.3 Problems of Light Pollution

The nocturnal ecosystems might be affected by light pollution due to such widespread usage. There have to exist good trap designs that spill as little light as possible and are used minimally.

7. FUTURE DIRECTIONS

7.1 Tailoring Light Wavelengths

Research into species-specific wavelength preferences can improve the precision and efficacy of light-based pest control.

7.2 Integration with Smart Farming

Integrating AI-driven phototaxis strategies with smart farming technologies enables real-time pest monitoring and adaptive management, enhancing agricultural productivity.

7.3 Environmental Considerations

Sustainable designs, such as energy-efficient traps and eco-friendly materials, are vital to minimizing the environmental footprint of phototaxis-based pest control.

8. CONCLUSION

Combined with AI-driven technology, insect phototaxis continues to be a useful tool in pest management, ushering in a new era of innovation. Utilizing biological insights, cutting-edge materials, and intelligent algorithms can improve the targeting, effectiveness, and environmental sustainability of pest control methods. Continued research and development are essential to address challenges and unlock the full potential of this approach.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. Grammarly
2. Copilot

COMPETING INTERESTS

Authors have declared that no competing interests exist

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