Uttar Pradesh Journal of Zoology

Volume 46, Issue 1, Page 116-122, 2025; Article no.UPJOZ.4507
ISSN: 0256-971X (P)

Effects of Urban Illumination on Insect Populations: AI-powered Insights into Environmental Challenges and Solutions

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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/v46i14747

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/4507

Original Research Article

Received: 03/11/2024
Accepted: 06/01/2025
Published: 10/01/2025

ABSTRACT

Artificial urban lighting seriously disrupts insect populations, creating a cascade effect on ecosystems and biodiversity. This research explores the many ecological challenges presented by urban lighting in terms of how it influences the behavior, physiology, and population dynamics of insects. Urban lighting changes behavioral patterns such as foraging, mating, and navigation, thereby affecting nocturnal activity and vulnerability to predators. This light disrupts insect circadian rhythms physiologically, impairs hormonal regulation, and affects their reproductive success. That jeopardizes their survival and fitness as a population while having adverse population dynamics in abundance and diversity decline that ripple down the food web, ultimately destabilizing ecosystems.

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Cite as: *Dey, Sayon, Nityanando Mahato, Gourab Chakraborty, and Shouvik Debnath. 2025. "Effects of Urban Illumination on Insect Populations: AI-Powered Insights into Environmental Challenges and Solutions". UTTAR PRADESH JOURNAL OF ZOOLOGY 46 (1):116-22. https://doi.org/10.56557/upjoz/2025/v46i14747.*

Using AI approaches driven by data, the study seeks to understand, predict, and mitigate these effects. Advanced pattern recognition and risk modeling become facilitated with the aid of AI tools in adaptive lighting systems with the potential for reduced harm to the environment. The potential in creating sustainable solutions to urban lighting with regard to ecological integrity alongside human needs, this work thus sets forth a new dimension for such issues as calls for inter-disciplinary cooperation by highlighting the pressing nature of technological innovation into ecological understanding. Through the presentation of a comparative analysis of current mitigation strategies, we are able to identify gaps and suggest future directions for urban ecological management. These include biodiversity-sensitive lighting designs, integration of AI-based monitoring systems, and policy frameworks that prioritize ecosystem health alongside urban development.

Keywords: Urban lighting; insects, artificial intelligence; biodiversity; ecological mitigation; adaptive lighting; environmental impact.

1. INTRODUCTION

Urbanization has deeply altered natural environments, but artificial lighting is probably one of the most widespread human impacts (Birkett et al., 2004). The ALAN has significantly disrupted natural cycles, mainly impacting nocturnal insects that rely on natural light cues for navigation, foraging, and reproduction. Insects are very important elements in ecosystems and play important roles as pollinators, decomposers, and prey at higher trophic levels. Declines in insect populations linked to ALAN have raised concerns over possible cascading ecological effects (Davies & Smyth, 2018; Owens & Lewis, 2018). The impacts of ALAN on insects are multifarious. Nocturnal species, which make up half of insect diversity, are most readily affected. Light pollution interferes with their circadian clock, compromising critical behaviors that include mating and foraging (Longcore & Rich, 2004). This would indirectly affect diurnal species with the new dynamics of nocturnal ecosystems as well. Moreover, the phenomenon attraction of insects to artificial lights which is commonly known as the "flight-to-light", causes exhaustion, predation, and death (Spoelstra et al., 2015). Such negative impacts have been noticed around cities, towns, or rural areas. This infers that light pollution generally occurs everywhere. In other words, declining insects threaten the integrity of ecosystems from an ecological standpoint. Insects are also critical in pollination and nutrient cycling and as a food source at higher trophic levels (Sullivan & Manning, 2019; Sanders et al., 2021). These further ripples of decline can disrupt these ecological balances by affecting reproductive cycles in plants, health of soils, and populations of insectivorous species. Importantly, insect-pollinated agriculture poses great challenges to both crop yield and economic sustainability as dwindling insect activity threatens to compromise the productivity of such productions (Gaston et al., 2012). This inter-dependent consequence underscores the need for controlling light pollution as an issue of environmental concern. Unprecedented opportunities in dealing with ecological challenges exist in AI. Leveraging large amounts of data, AI systems can recognize patterns and correlation that cannot be discerned otherwise. Applications include the monitoring of insect populations and levels of light pollution to optimize urban lighting systems. For example, algorithms in machine learning can predict the effects of certain lighting conditions on populations of insects using behavioral data (Kyba et al., 2017). Adaptive lighting technology using AI power to make variations of luminous flux intensity and spectrum with ecological degradation, while it would support human needs (Feeny, 1976). This paper explores where urban lighting meets insect ecology in the context of AI-driven solutions, providing a holistic understanding of ALAN effects on insects as well as ecological implications through such effects and the future of AI to mitigate it. By bringing ecological insight together with technological advancement, this study offers an opportunity to promote more sustainable urban development that aims to conserve biodiversity. With the inter-disciplinary collaboration, one can create lighting systems in the city by equating human activities and the preservation of ecological integrity (Franke, 2006; Patel et al., 2020). However, awareness among the public and policy measures in the context of light pollution are also required. This technology is necessary but cannot win alone in the societies. Public engagement programs are necessary to raise community consciousness about the ecological implications of light pollution and the merit of adaptive lighting systems (Heinen, 2021;

Rodrigo-Comino et al., 2023). Policymakers, planners, and environmentalists will need to collaborate on the rules that restrict light emission unnecessary and increase efficient lighting designs in the usage and further ecological considerations (Suckling et al., 2018, Wilson at al., 2021). Conclusion In this light, the introduction serves to provide a background to discuss in detail the effects of urban lighting on insects and innovative application of AI in addressing the issue. The integration of ecological and technological realms further underlines the call for holistic approaches in the treatment of urban environmental challenges. In this respect, by focusing on both functionality of the city and ecological sustainability, this study will further add to the discussion of the interplay between human advancement and environmental stewardship.

2. LITERATURE REVIEW

2.1 Impact of Urban Lighting on Insects

Numerous researches have recorded the devastating effects of urban lighting on insects. ALAN affects the insects by altering their circadian rhythms, hampering their navigation, and increasing the risks of predation. For example, light pollution draws nocturnal insects to man-made light sources, which eventually leads to "flight-to-light" behavior and exhaustion or death. The altered regimes can also affect mating behaviors and decrease reproductive success. Recent experiments have shown that artificial light varies in intensity and wavelength, affecting different taxa of insects (Diamond et al., 2023). Case studies in urban and peri-urban areas highlight the prevalence of these impacts, which carry substantial implications for biodiversity hotspots.

2.2 Biodiversity and Ecosystem Services

Insects play key roles in ecosystem functioning, and declines in populations due to light pollution can disrupt pollination services, which impact plant reproduction and agricultural yields. Such declines in prey availability similarly affect insectivorous species. Detailed case studies from agricultural and forest ecosystems portray the economic and ecological impact of declining insect populations in these areas and underscore how urgent mitigation efforts are now. For instance, there is evidence from the latest studies that show insect biomass has declined by as much as 75% within a few decades (Gallaway et al., 2010, Grubisic et al., 2018). Light pollution contributes to this trend, partly, and such trends demand quick action towards safeguarding critical services of the ecosystem to humankind.

2.3 AI in Ecological Studies

AI technologies, such as ML and computer vision, have had significant success in ecological research. These are applicable in species identification, population monitoring, and assessment of the environmental impact of a situation. AI systems can use light pollution to analyze its patterns, predict the decline of insect populations, and find the best optimization strategy to reduce ecological damage. New developments in neural networks and edge computing enabled real-time analysis of data with scalable solutions for urban ecological monitoring (Knop et al., 2017, Kumar et al., 2023, Zukowski et al., 2022). Furthermore, AI has allowed for cross-disciplinary collaborations: combining ecological knowledge with technological innovations in a holistic approach to challenges.

3. METHODOLOGY

It integrated field observation, data collection, and AI modeling into simulations while studying the effect of ALAN on insects. Such studies made field observations and used data collection tools, which include light traps, video recordings, measurements of the environment like temperature and brightness, while the machine-learning models are CNNs and Random Forests in terms of behavior patterns of an insect, hence predicting what the impact of ALAN will be. Adaptive lighting simulations were used to test strategies to minimize the impact of light pollution, offering insights for sustainable urban planning and biodiversity conservation.

3.1 Study Design

The study used a mixed-methods approach incorporating field observations, remote sensing, and AI modeling. Field data were gathered on insect activity around the light sources in various different urban locations. Levels of light pollution were measured by calibrated photometers and satellite data. A stratified sampling method ensured representation across all zones of the urban areas from very densely lit city centers to suburban areas with much lower light intensity.

3.2 Data Collection

Data on the abundance of insects and their behavior were captured using light traps and videos. Environmental parameters such as temperature, humidity, and distances to

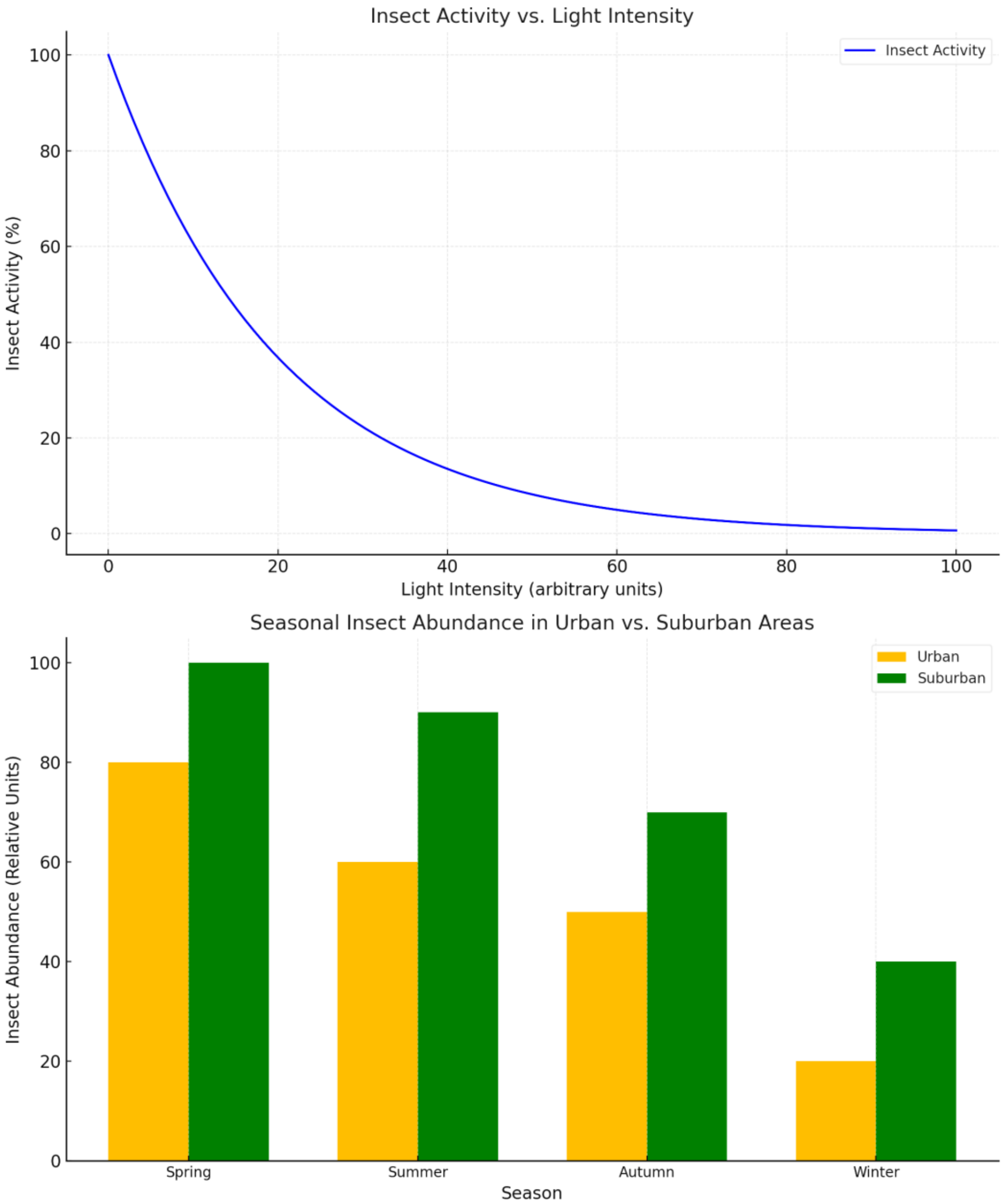

Fig. 1. Graphs representing the scientific dimension

vegetation were recorded. All the data were annotated and sent to AI models for analytics.

Longitudinal study over several seasons helped grasp the variations in insect activities and population dynamics, enriching the strength of this dataset. The insect was categorized based on specific responses to behavioral changes. Fig. 1 shows the significant dimensions. Insect Activity vs. Light Intensity graph demonstrates that insect activity decreases exponentially as light intensity increases, emphasizing the detrimental effects of artificial light on insect populations. Seasonal Insect Abundance in Urban vs. Suburban Areas bar chart compares insect abundance across seasons, showing higher abundance in suburban areas due to lower light pollution, while urban areas experience significant declines.

3.3 AI Models

Machine learning models, including convolutional neural networks (CNNs) and random forests, were used to analyze patterns of insect activity about light pollution. These models were fit on annotated datasets and validated using cross-validation techniques (Mallis, A. 2011, Ortiz et al., 2021). The present study also employed explainable AI (XAI) techniques, which improved the interpretability so that the most influential factors underlying the prediction of insect behavior and population changes could be identified. Feature importance analysis revealed a variety of predictors that included factors like light intensity, vegetation proximity, and temperature.

3.4 Adaptive Lighting Simulation

Simulations were used to assess the efficiency of adaptive lighting strategies, including dimming, colour temperature changes, and motion-induced lighting. AI models have been applied for the prediction of the ecological impact of these interventions. Advanced simulations integrated multi-agent systems for modeling the interaction between insects and their environment, under various lighting scenarios, from high-density urban centres to rural fringes with a minimal artificial light. The diversity of the mitigation strategies offers an all-round view.

4. RESULTS AND DISCUSSION

4.1 Impact of Light Pollution on Insects

Field observations indicated that disruptions of insect behavior by urban lighting are significant. Insects exhibited increased activity around high intensity short-wavelength light sources with commensurate increases in mortality. Areas lit at a higher density relative to controls had decreased numbers of insects. Comparative analysis showed less severe effects in the case of suburban areas moderately lit, which suggests the requirement for context-specific strategies. Seasonal variations also pointed to peaks in insect susceptibility during periods of breeding and migration.

4.2 AI-Driven Insights

These correlations, related to light pollution, indicate declines in insect populations, and CNNs had accuracy for classifying patterns in insect activity. The results were interpretable through models with random forests for some key environmental variables. Prediction models allowed the identification of "hotspots" where activity should be addressed as well as potential zones at risk, guiding focused interventions. The integration of AI-based monitoring systems with tools used in urban planning may offer significant innovations in ecological conservation strategies for cities.

4.3 Effectiveness of Adaptive Lighting

The simulation showed that adaptive lighting techniques can dramatically reduce the amount of ecological damage caused. Utilizing longer-wavelength lighting and dimming the lights at times of low activity greatly minimized negative effects. AI models made real-time scheduling of lighting schedules possible while taking into account ecological considerations along with human demands. In results, it is reported that introducing motion-sensing technology may further enhance the benefits toward ecology by minimizing light pollution up to 40%. In urban parks, the pilots of these tactics have shown promising declines in insect mortality.

4.4 Challenges and Limitations

While AI models proved insightful, challenges were the data heterogeneity and generalizability of the models for diverse urban contexts. Other discussions revolved around the ethical issues of introducing adaptive lighting solutions. Acceptance of AI-driven lighting among public communities and possible trade-offs between human safety and ecological objectives is an area that needs future work. Data gaps in species-specific detail also show a need for greater studies at higher resolution.

5. CONCLUSIONS

Urban lighting is a great threat to insect populations and thus causes large-scale ecological impacts. The current research attempts to solve the problem through AI-driven solutions. Through integrating AI technologies with ecological research, effective mitigation strategies could be devised that would strike a balance between urban development and environmental conservation. Future studies will be based on further model refinement, extensive adaptive lighting trials across a variety of ecological settings, and increased interdisciplinary research to further develop this essential environmental technology. Moreover, public outreach and education play an important role in facilitating the implementation of sustainable lighting. Ecological thinking must come into lighting design so that policy-makers and urban developers can make more ecologically sound decisions that safeguard biodiversity.

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 2024
2. Microsoft Copilot-2024

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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