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HAWKMOTH POLLINATION UNDER ARTIFICIAL LIGHT: EXAMINING THE IMPACTS ON FORAGING, FLORAL VISITATION, AND REPRODUCTIVE SUCCESS

Jennica Joy Lopena[1]
Mikaela Loraine Jermice[1]
Ashley Gabrielle A. Robis[1]
Gecelene C. Estorico[1, 2]
Civil and Allied Department; Environmental Science and Chemical Technology Department
[1]Technological University of the Philippines—Taguig, Taguig, Metro Manila 1630 Philippines
[2]De La Salle University – Dasmariñas, DBB-B, 4115 West Ave, Dasmariñas,

ABSTRACT
Artificial light pollution has emerged as an aggravating environmental issue, particularly affecting nocturnal pollinators like hawkmoths. These insects are essential for plant reproduction by enabling nocturnal pollination. Nonetheless, heightened artificial lighting interferes with their foraging behavior, diminishes floral visitation rates, and adversely affects plant reproductive success. This systematic analysis analyzes the impact of artificial light on hawkmoth pollination, focusing on foraging efficiency, pollination rates, and species-specific effects. In accordance with the PRISMA criteria, pertinent papers published in the past five years were examined to consolidate essential data about the influence of light intensity and spectral composition on nocturnal pollination. The analysis indicates that artificial illumination reduces flower visitation by as much as 62%, with increased light intensities and short-wavelength lights (such as blue and white LEDs) producing the greatest interference. Pollination efficacy declines by 30–40% in light-exposed flora, resulting in reduced seed and fruit yield in species such as *Oenothera biennis*, *Datura wrightii*, and *Agave palmeri*. These findings underscore the imperative necessity for conservation strategies, such as reducing artificial light intensity, transitioning to red-spectrum illumination, and enforcing light curfews in critical pollination environments.

Keywords:
Artificial Night Lighting, Conservation Strategies, Foraging Efficiency, Hawkmoth Behavior, Light Pollution Effects, Nocturnal Pollinators

INTRODUCTION

Artificial light pollution is a significant environmental concern that has vital ecological consequences, specifically for nocturnal pollination systems. As anthropogenic alterations persist in altering ecosystems, more study is being directed towards the disturbance of essential ecological relationships, particularly between nocturnal pollinators and flora. Hawkmoths (family *Sphingidae*) foster biodiversity conservation by enabling nocturnal pollination. Artificial lighting disrupts the natural behaviors of nocturnal pollinators, leading to diminished pollination success and potential reproductive adverse consequences for plant species reliant on these pollinators (Knop et al., 2020; Macgregor et al., 2020). Numerous studies have shown that artificial light influences hawkmoth foraging behavior and patterns of flower visitation. Nocturnal pollinators exhibit heightened sensitivity to artificial light, which can hinder the capacity to locate flowers and facilitate pollen transfer (Elliott et al., 2021). Moreover, tree cover and many environmental factors influence the interaction of artificial light with pollination systems, either mitigating or exacerbating the effects (Knop et al., 2021). These findings highlight the imperative necessity for a comprehensive analysis of how artificial light disrupts nocturnal pollination networks. In addition to light pollution, hawkmoth populations face other anthropogenic issues, including habitat fragmentation, temperature change, and chemical poisoning. Documented declines in pollinator populations have generated concerns over their cascading effects on plant reproductive success and the general stability of ecosystems (Tucker & Rehan, 2021). Understanding the impact of artificial lighting on hawkmoth pollination is essential to establishing effective conservation strategies to alleviate biodiversity loss. Harrison et al. (2021).

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OBJECTIVES

This systematic review aims to synthesize current research on the impact of artificial light pollution on hawkmoth pollination, focusing on key factors including foraging behavior, floral visitation rates, and plant reproductive success. This review will offer a comprehensive analysis of the implications of artificial light on hawkmoth-mediated pollination and identify existing knowledge gaps (Elliott & Hemberger, 2021). The review centers on the notion of ecological light pollution, which asserts that artificial lighting interferes with natural behaviors by influencing species relationships and physiological processes (Grenis & Murphy, 2020). The primary objectives of this study are to (1) ascertain the influence of artificial light on hawkmoth foraging behavior, (2) assess its implications on floral visitation and pollination efficacy, and (3) propose conservation strategies to mitigate these impacts. The study's framework seeks to contribute to the expanding array of literature on nocturnal pollination ecology and promote sustainable lighting strategies that integrate human growth with biodiversity conservation.

METHODOLOGY

A. Research Methodology

This work employs a systematic review methodology to consolidate existing knowledge on the effects of artificial light pollution on hawkmoth pollination, foraging behavior, and plant reproductive performance. The evaluation technique will comply with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Page et al., 2021) to ensure transparency, rigor, and reproducibility. The review will include peer-reviewed journal publications and relevant gray literature from reputable scientific sources, focusing on studies published in the past five years.

B. Data Acquisition

A thorough literature assessment will be performed using databases such as Web of Science, Scopus, Google Scholar, and ResearchGate to ensure a robust and diverse collection of relevant studies. The search will encompass specific terms and Boolean operators, such as "hawkmoth pollination" AND "artificial light pollution," "nocturnal pollination" AND "light exposure," and "foraging behavior" AND "pollinator decline."

Studies will be selected based on the following inclusion criteria: they must be peer-reviewed articles or reports published in English from 2019 onward, focus on hawkmoth pollination under artificial light conditions, and examine foraging behavior, floral visitation rates, and reproductive success. Research will be rejected if it is irrelevant to pollination ecology or nocturnal pollinators, or if it provides insufficient data or lacks empirical evidence. The evaluation process will consist of two phases: an initial assessment of the title and abstract, followed by an extensive study of the whole text. Only studies meeting the specified inclusion criteria will be incorporated into the final analysis (Hölker et al., 2020). Data pertinent to each chosen study will be methodically extracted to facilitate comparative analysis. The collected data will include study location and environmental conditions; type and intensity of artificial light exposure; examined pollinator species; floral visitation rates and foraging behavior metrics; and plant reproductive outcomes, such as fruit set and seed production (Elliott & Hemberger, 2021).

C. Data Collection

Studies meeting the inclusion criteria will be systematically categorized based on their methodology, species analyzed, and key findings to ensure a structured and comprehensive review. This strategy will enable the recognition of patterns, discrepancies in experimental techniques, and existing deficiencies in the literature regarding artificial light pollution and hawkmoth pollination. Specific attention will be focused on the influence of differing light conditions on hawkmoth feeding behavior, floral visitation rates, and plant reproductive success. This study seeks to elucidate the significant ecological impacts of artificial light pollution on nocturnal pollination systems through data integration. The results will offer significant insight into pollinator conservation and the alleviation of human-induced disruptions to nocturnal ecosystems.

D. Data Analysis

Descriptive statistics will encapsulate variability in floral visitation, foraging habits, and reproductive outcomes. A comparison analysis will be performed to determine the degree of variation in responses across diverse environmental conditions. Regression models will be employed, if applicable, to assess the correlation between artificial light intensity and pollination success. Sensitivity analysis will identify inconsistencies in results among studies (Macgregor et al., 2020). This systematic approach seeks to deliver a thorough assessment of the impact of artificial light on hawkmoth pollination and to inform conservation strategies that mitigate adverse consequences.

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RESULTS AND DISCUSSION

A. Overview of Research on the Impact of Artificial Illumination on Hawkmoths

Artificial light at night (ALAN) has emerged as a growing environmental issue, especially regarding its impact on nocturnal pollinators and insects. Various research has investigated the effects of light pollution on species behavior, pollination rates, and ecological relationships. The studies encompassed in this matrix elucidate the effects of varying light intensities and spectra on nocturnal species, including moths and other insects vital for nighttime pollination. The table below encapsulates essential research findings, detailing the species examined, geographical locales, experimental light intensities, and the principal ecological ramifications discovered. These investigations collectively underscore the extensive disruptions induced by artificial lighting, ranging from diminished pollination efficacy to modified foraging habits and species interactions.

Author/s and Year	Focus of the Study	Key Findings/Results
Bennie et al. (2020)	Field studies in the UK on wild plants exposed to 5, 10, and 20 lux.	Artificial light altered growth patterns and pollination dynamics.
Davies et al. (2022)	UK field and lab studies on various species and their responses to blue-rich vs. amber and red lights.	Changes in light spectrum favor some species over others, altering interactions.
Eisenbeis & Eick (2020)	Field observations in Germany comparing nocturnal insect attraction to LEDs vs. traditional lights.	LEDs attracted fewer insects than traditional lights but still disrupted insect behavior.
Firebaugh & Haynes (2020)	Experimental field tests in the USA on nocturnal insects using light intensities of 5–50+ lux.	Artificial light disrupted courtship behaviors and reduced dispersal distances.
Gaston et al. (2023)	Global theoretical review of multiple taxa on light intensities from <1 to 100+ lux.	Light pollution alters behavior and ecological interactions across species.
Knop et al. (2020)	Field experiments in Switzerland on nocturnal pollinators under 0, 10, and 20 lux.	Artificial light reduced pollinator visits by 62%, leading to a 13% reduction in fruit set.
Macgregor et al. (2020)	Review of global studies on nocturnal Lepidoptera and pollination, using 1–50+ lux.	Light pollution negatively impacts moth pollination, reducing pollination efficiency.
Owens & Lewis (2020)	Global review on nocturnal insects with intensities of 1–50+ lux.	Light pollution disrupts nocturnal insect navigation and reproduction.
Sanders et al. (2021)	Meta-analysis of global studies on various taxa using 1–100+ lux.	Artificial light has widespread negative effects across different species.
Van Langevelde et al. (2021)	Light trap experiments in the Netherlands on moths using different light spectra (UV to red).	Moths were more attracted to UV and blue lights than to longer wavelengths.

Table 1. Summary of Studies on the Effects of Artificial Light at Night (ALAN) on Insects, Pollinators, and Plants

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B. Disruptions in Foraging Efficiency

Foraging efficiency is a vital component of hawkmoth activity, as these nocturnal pollinators depend on their visual and olfactory senses to identify and consume flowers. Artificial light at night (ALAN) alters natural foraging rhythms, resulting in delayed activity, prolonged search time, and diminished eating efficiency. Exposure to artificial illumination modifies their circadian rhythms, resulting in delayed foraging behavior. Macgregor et al. (2019) noted that hawkmoths exposed to streetlights commenced their foraging behavior up to 45 minutes later than those in natural darkness. This delay reduces the time available for feeding and pollination, which poses significant challenges for plant species that rely predominantly on hawkmoths for reproductive success. Furthermore, competition with diurnal pollinators escalates, since nectar stores may be exhausted by bees and butterflies prior to the foraging activities of hawkmoths. Consequently, hawkmoths are compelled to allocate additional time to locate flowers, so diminishing their feeding efficacy.

Artificial illumination prolongs the duration necessary for hawkmoths to identify flowers. Hawkmoths generally rely on olfactory and optical signals to locate nectar-abundant flora; however, artificial illumination modifies these signals, complicating their foraging efforts. Intense artificial illumination, especially from streetlights generating blue and white wavelengths, disrupts hawkmoths' perception of flower hues, resulting in bewilderment and distraction (Grenis & Murphy, 2020). Furthermore, flowers that often contrast with a dark background in natural settings become more difficult to discern under artificial lighting, rendering them less visually appealing to pollinators. Hawkmoths subjected to artificial illumination frequently display irregular flying behaviors, lingering for prolonged durations prior to making foraging choices. This ineffective locomotion leads to diminished visitation rates, with research indicating that hawkmoths in artificially illuminated settings visit up to 62% fewer flowers per night than those in dark conditions (Knop et al., 2020).

A major effect of diminished foraging efficiency is a decrease in nectar consumption, potentially resulting in energy shortages. Hawkmoths depend on nectar as their principal energy source for flight and reproduction, and disturbances in their feeding habit can adversely affect their survival and reproductive success. Owens et al. (2020) discovered that hawkmoths in artificially illuminated settings ingested 40% less nectar nightly compared to those in unlit situations. The inadequate energy intake debilitates hawkmoths, diminishing their capacity to traverse extensive distances in pursuit of sustenance and mates. Hawkmoths possess elevated metabolic requirements owing to their fast wingbeats, and these energy deficiencies may lead to diminished mating success, ultimately jeopardizing population stability.

The impairments in hawkmoth feeding efficiency have far-reaching consequences on entire ecosystems, especially with pollination networks. Numerous plant species depend only on hawkmoths for pollination; a decrease in foraging efficiency leads to diminished pollen transfer, reduced fruit set, and an overall fall in plant populations. Moreover, hawkmoths serve as a crucial aliment for nocturnal predators, like bats and owls. A decline in hawkmoth populations resulting from inadequate energy acquisition and diminished reproductive success may precipitate food shortages for these predators, so disrupting the food web equilibrium. The behavioral modifications are summarized in Table 2, which delineates the impact of augmented light intensity on hawkmoth foraging efficiency.

Light Intensity (lux)	Average Search Time (seconds)	Hovering Duration (seconds)	Resting Frequency (events per minute)	Flower Visitation Rate (flowers per hour)
0 (Natural Darkness)	8.5	4.2	1.1	14.8
5 lux	12.1	6.8	2.4	11.2
10 lux	18.3	9.7	3.8	7.5
20 lux	25.6	12.5	5.2	4.3
50 lux	34.8	16.2	7.1	2.1

Table 2. Effects of Light Intensity on Hawkmoth Foraging Behavior Adapted from Macgregor et al. (2020) and Knop et al. (2021)

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The table above shows the impact of light intensity on hawkmoth foraging behavior, indicating that heightened artificial light impairs their efficiency. As light intensity increases, the average search time for flowers escalates markedly, from 8.5 seconds in complete darkness to 34.8 seconds at 50 lux. Correspondingly, the duration of hovering also escalates, indicating heightened difficulty in managing flowers.

Furthermore, the table indicates that resting frequency escalates under elevated light settings, suggesting heightened energy expenditure or potential confusion. The flower visitation rate significantly declines from 14.8 flowers per hour at 0 lux to merely 2.1 at 50 lux. This fall indicates a decrease in pollination efficacy, which may impact plant reproduction in nocturnal settings.

C. Temporal Shifts in Foraging Activity

Artificial light not only reduces the foraging effectiveness of hawkmoths but also modifies the sequence of their foraging behavior, resulting in a substantial mismatch between pollinators and nocturnal flowering plants. Numerous nocturnal flowers have adapted to secrete nectar at designated times of the nighttime to align with the behavior of their principal pollinators, so assuring effective reproduction. The existence of artificial lighting interrupts this synchronicity by postponing the commencement of hawkmoth feeding, hence diminishing pollination rates in plant species dependent on early-night visits from these nocturnal pollinators (Macgregor et al., 2020; Grenis & Murphy, 2020).

In natural darkness, hawkmoths generally initiate foraging between 20:00 and 23:00, coinciding precisely with the peak nectar supply of numerous nocturnal plants. Nonetheless, exposure to differing concentrations of artificial light induces a gradual alteration in their foraging schedules. At a moderate light intensity of 5 lux, hawkmoth foraging is postponed until 21:00–00:00, and at 10 lux, their activity is further deferred until 22:00–01:00. As the illumination reaches 20 lux, foraging is deferred to 23:00–02:00, and at 50 lux or above, hawkmoths may not commence foraging until 00:00–03:00. These delays significantly diminish the synchronization between hawkmoth activity and the peak nectar availability of nocturnal flowers, resulting in reduced pollination efficacy and diminished reproductive success for plants reliant on early-night pollination.

In addition to modifying foraging schedules, artificial light results in a general reduction in hawkmoth activity, thus impacting pollination networks. Research indicates that the presence of hawkmoths diminishes by 15% under artificial light at 5 lux, by 30% at 10 lux, and by up to 50% at 20 lux. At levels exceeding 50 lux, hawkmoth activity diminishes by an astonishing 70%, substantially restricting their capacity to pollinate nocturnal flora (Hölker et al., 2020). The reduction in hawkmoth populations, along with postponed foraging periods, leads to diminished nocturnal flower visits, hence decreasing pollen transfer and jeopardizing the reproductive viability of several plant species dependent on hawkmoths as their principal pollinators.

Light Intensity (lux)	Foraging Start Time	Foraging End Time	Activity Reduction (%)
0 (Natural Darkness)	20:00	23:00	0%
5 lux	21:00	00:00	15%
10 lux	22:00	01:00	30%
20 lux	23:00	02:00	50%
50 lux	00:00	03:00	70%

Table 3. Shifts in Foraging Activity Under Artificial Light
Adapted from Macgregor et al. (2020) and Grenis & Murphy (2020)

The table above indicates the effect of artificial light on hawkmoth foraging activity, indicating a marked alteration in their active periods and a substantial decrease in overall foraging behavior.

As light intensity escalates, the initiation and conclusion of foraging activities are postponed. In complete darkness (0 lux), hawkmoths commence foraging at 20:00 and conclude at 23:00. Foraging commences at 00:00 and concludes at 03:00 when illumination is below 50 lux, a delay of four hours. This alteration presumably

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diminishes the concurrence between hawkmoth activity and the apex nectar secretion of flowers, thus impacting pollination efficacy.
The data indicates that foraging activity diminishes with increasing artificial light intensity. At 5 lux, activity diminishes by 15%, whereas at 50 lux, a 70% decrease is noted. This decrease indicates that enhanced artificial illumination deters hawkmoth foraging, presumably due to disorientation or avoidance behavior.

D. Effects of Light Spectrum on Foraging Behavior

The impact of artificial illumination on hawkmoth foraging behavior is significantly hinged on the spectral content of the light source. Artificial light wavelengths exert differing effects on nocturnal pollinators, with certain wavelengths proving more disruptive than others. Studies demonstrate that blue and white LED lights, which generate a substantial amount of short-wavelength light, significantly disrupt hawkmoth activity. These wavelengths are very appealing to moths, frequently enticing them from their usual foraging areas and redirecting their movement away from flowering plants. The attraction to artificial light sources diminishes pollination efficiency, since hawkmoths allocate less time to flower visitation and more time hovering near artificial light fixtures. Consequently, plants dependent on hawkmoth pollination exhibit diminished reproductive success, potentially impacting plant populations and environmental stability (Elliott & Hemberger, 2021).
Conversely, artificial light sources emitting in the red spectrum have demonstrated negligible effects on hawkmoth behavior. Moths, akin to numerous other nocturnal insects, exhibit reduced sensitivity to longer wavelengths, indicating that red light does not substantially attract or disorient them. This diminished sensitivity enables hawkmoths to preserve their innate foraging behaviors, hence enhancing the probability of successful pollination occurrences. Research indicates that employing red-spectrum lighting in regions with significant pollinator activity may work as a mitigation technique, alleviating the adverse effects of artificial light pollution while yet ensuring adequate illumination for human endeavors (Stone et al., 2020).

Light Spectrum	*Attraction to Artificial Light (%)*	*Floral Visitation Rate (flowers/hour)*
Darkness	0%	14.8
Red Light	5%	13.9
Green Light	15%	11.4
White LED	60%	5.8
Blue LED	75%	3.2

Table 4. Effects of Light Spectrum on Hawkmoth Floral Visitation
Adapted from Owens et al. (2020) and Elliott & Hemberger (2021

The table above illustrates the impact of various light spectra on hawkmoth attraction to artificial light and their rates of floral visits. The table indicates that attraction to artificial light intensifies with decreasing wavelengths. Hawkmoths exhibit no attraction to artificial light sources in darkness (0%). Under blue LED light, attraction increases to 75%, markedly distracting them from their typical foraging behavior. White LED light significantly attracts 60% of hawkmoths. Conversely, red light exerts minimal influence, attracting merely 5%, indicating that longer wavelengths are less perturbative.
The table reveals that floral visitor rates diminish as the attraction of artificial light increases. In darkness, hawkmoths visit 14.8 flowers every hour; however, under blue LED light, their attendance significantly declines to 3.2 flowers per hour. Under white LED illumination, the rate diminishes markedly to 5.8 blooms per hour. This indicates that artificial light, particularly in the blue and white spectrum, interferes with feeding by diverting hawkmoths from flowers.

E. Reduction in Pollination Success

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The disruptions induced by artificial light—namely prolonged search duration, postponed foraging behavior, and alterations in spectral attraction—cumulatively result in a notable reduction in pollination efficacy. Hawkmoths are integral to pollination networks, especially for nocturnal plant species that depend on their nighttime feeding activities. Nevertheless, artificial light disrupts pollinators' capacity to discover and access flowers effectively, resulting in repercussions that reach beyond particular species to the wider ecosystem.

Numerous studies have recorded a 30–50% reduction in seed production among plant species mostly pollinated by hawkmoths when subjected to artificial light (Knop et al., 2021). This fall is chiefly attributable to the reduction in floral visitation rates, which diminishes the transmission of pollen between flowers. In certain instances, plant species that depend significantly on hawkmoth pollination encounter pollen constraint, resulting in a reduced number of fertilized ovules and, consequently, diminished fruit and seed production (Macgregor et al., 2020).

The quality of pollination is also impacted. Hawkmoths exhibit modified foraging behavior, including prolonged lingering and irregular flying patterns, while visiting flowers under artificial light, resulting in poor pollen transmission. Certain studies indicate that artificial illumination diminishes the quantity of pollen transferred per visit, hence impairing reproductive success in plants reliant on particular hawkmoth species for efficient pollination (Grenis & Murphy, 2020).

The reduction in pollination efficacy has far-reaching ecological repercussions. Numerous plant species pollinated by hawkmoths are essential nectar supplies for other pollinators, such as bees and butterflies, during daylight hours. A decrease in seed production may lead to diminished plant population densities, ultimately impacting the overall pollination network. In agricultural settings, crops dependent on nocturnal pollinators—such as specific varieties of squash, tobacco, and agave—may suffer diminished yields and decreased genetic diversity in their progeny due to inadequate cross-pollination (Elliott & Hemberger, 2021).

Plant Species	Seed Production (Natural Darkness)	Seed Production (Artificial Light)	% Reduction
Agave palmeri	85%	50%	41%
Datura wrightii	92%	57%	38%
Oenothera biennis	78%	45%	42%
Mirabilis jalapa	88%	52%	41%
Nicotiana attenuata	80%	48%	40%

Table 5. Decline in Seed Production Under Artificial Light
Adapted from Macgregor et al. (2020) and Knop et al. (2021)

The table above concisely indicates that artificial light markedly diminishes seed production in plants dependent on nocturnal pollination. For all enumerated species, seed production diminishes by 38% to 42% under artificial light, signifying a significant disruption in their reproductive efficacy. For example, *Agave palmeri* has a 41% decrease, whilst *Oenothera biennis* undergoes the most significant fall at 42%. This persistent trend indicates that artificial illumination adversely affects numerous night-pollinated plant species, presumably due to less pollinator activity.

The reduction in seed production corresponds with earlier research indicating that artificial light diminishes hawkmoth floral visitation rates. A reduction in visits markedly decreases the likelihood of successful pollination, resulting in less seed production. As these plants rely on nocturnal pollinators such as hawkmoths, the interference from artificial light directly impacts their reproductive capacity and population viability. This trend underscores the essential function of nocturnal pollinators in sustaining plant reproductive efficacy and environmental equilibrium.

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These findings indicate wider ecological implications beyond particular plant species. Decreased seed production may result in diminishing plant populations, reduced biodiversity, and compromised ecosystems. Moreover, species dependent on these plants for sustenance or habitat may also be impacted, resulting in cascading impacts across the food chain. The significance of these plants in sustaining wildlife and preserving environmental equilibrium renders the noted declines in seed production concerning regarding the long-term implications of light pollution.

These findings underscore the essential importance of safeguarding dark settings to sustain the fragile ecological equilibrium between nocturnal pollinators and flowering plants. Mitigation techniques, including the reduction of artificial light intensity and the implementation of red-spectrum lighting, may alleviate the detrimental impacts on hawkmoth populations and their pollination services. With the global proliferation of artificial light pollution, additional research is needed to formulate conservation strategies that safeguard nocturnal environments and preserve biodiversity.

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CONCLUSION

Artificial light pollution significantly disrupts with the foraging behavior and pollination efficacy of hawkmoths, resulting in ecological consequences for nocturnal plant species. The delay of foraging behavior caused by artificial illumination leads to a discord between pollinators and nocturnal flora, ultimately diminishing pollination efficacy. The research indicates that heightened light intensity exacerbates the problem by delaying foraging times into the night, resulting in a substantial decrease in hawkmoth activity. Moreover, distinct wavelengths of artificial light exert differing influences on hawkmoth activity, with blue and white LED lights causing the most disturbance, whilst red-spectrum light had negligible impacts.

These findings underscore the essential importance of safeguarding dark settings to sustain the fragile ecological equilibrium between nocturnal pollinators and flowering plants. Mitigation techniques, including the reduction of artificial light intensity and the implementation of red-spectrum lighting, may alleviate the detrimental impacts on hawkmoth populations and their pollination services. The proliferation of artificial light pollution worldwide necessitates additional research to formulate conservation strategies that safeguard nocturnal environments and preserve biodiversity.

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