

UNIVERSIDADE FEDERAL DE VIÇOSA

Influence of light conditions on the dynamics of *Tetranychus urticae* and its control by the predatory mite *Neoseiulus californicus*

Rodrigo Cardoso Silva
Magister Scientiae

**VIÇOSA - MINAS GERAIS
2025**

RODRIGO CARDOSO SILVA

Influence of light conditions on the dynamics of *Tetranychus urticae* and its control by the predatory mite *Neoseiulus californicus*

Dissertation submitted to the Entomology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Arnoldus R. Maria Janssen

**VIÇOSA - MINAS GERAIS
2025**

**Ficha catalográfica elaborada pela Biblioteca Central da Universidade
Federal de Viçosa - Campus Viçosa**

T

S586i
2025
Silva, Rodrigo Cardoso, 1995-
Influence of light conditions on the dynamics of
Tetranychus urticae and its control by preatory mite *Neoseiulus
californicus* / Rodrigo Cardoso Silva. – Viçosa, MG, 2025.
1 dissertação eletrônica (31 f.): il. (algumas color.).

Texto em inglês.

Orientador: Arnoldus Rudolf Maria Janssen.

Dissertação (mestrado) - Universidade Federal de Viçosa,
Departamento de Entomologia, 2025.

Referências bibliográficas: f. 27-31.

DOI: <https://doi.org/10.47328/ufvbbt.2025.459>

Modo de acesso: World Wide Web.

1. *Tetranychus urticae* - Efeitos da luz. 2. *Neoseiulus
californicus* - Efeitos da luz. 3. Ácaros no controle biológico de
pragas - Efeitos da luz. I. Janssen, Arnoldus Rudolf Maria,
1958-. II. Universidade Federal de Viçosa. Departamento de
Entomologia. Programa de Pós-Graduação em Entomologia.
III. Título.

CDD 22. ed. 632.6542

RODRIGO CARDOSO SILVA

Influence of light conditions on the dynamics of *Tetranychus urticae* and its control by the predatory mite *Neoseiulus californicus*

Dissertation submitted to the Entomology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

APPROVED: February 27, 2025.

Assent:

Rodrigo Cardoso Silva
Author

Arnoldus Rudolf Maria Janssen
Adviser

Essa dissertação foi assinada digitalmente pelo autor em 14/07/2025 às 11:56:43 e pelo orientador em 14/07/2025 às 13:24:20. As assinaturas têm validade legal, conforme o disposto na Medida Provisória 2.200-2/2001 e na Resolução nº 37/2012 do CONARQ. Para conferir a autenticidade, acesse <https://siadoc.ufv.br/validar-documento>. No campo 'Código de registro', informe o código **VK7G.KQMA.P82C** e clique no botão 'Validar documento'.

To my advisors, Arne and Angelo, for their invaluable guidance and mentorship, both
academically and professionally.

To my parents, Marcos and Anamalia, for always prioritizing my education and
supporting my dreams.

To my brother, my family and friends for their unwavering support and
encouragement.

To my partner, João, for always standing by my side and reminding me of the
beautiful things in life.

To my colleagues from the Acarology Lab and the Entomology department for the
time we shared working together.

To the Entomology Department for all the support.

To the Federal University of Viçosa, for the opportunity to pursue this postgraduate
degree.

To the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for
granting the scholarship.

ACKNOWLEDGMENTS

This work has been sponsored by the following Brazilian research agencies: Coordination for the Improvement of Higher Education Personnel (CAPES; Financing code 001), Minas Gerais State Foundation for Research Aid (FAPEMIG) and National Council of Scientific and Technological Development (CNPq).

“The truth. It is a beautiful and terrible thing, and should therefore be treated with great caution.” (Rowling, 1997)

ABSTRACT

SILVA, Rodrigo Cardoso, M.Sc., Universidade Federal de Viçosa, February, 2025. **Influence of light conditions on the dynamics of *Tetranychus urticae* and its control by the predatory mite *Neoseiulus californicus*.** Adviser: Arnoldus Rudolf Maria Janssen.

The increasing adoption of LED technology in agriculture raises important ecological questions regarding its impact on pest and natural enemy dynamics. This study investigates the impact of LED light exposure on the dynamics of the two-spotted spider mite (*Tetranychus urticae*) and its control by the predatory mite *Neoseiulus californicus*. Three light treatments were applied: natural light, 12h LED light and 12h dark, and continuous 24h LED light. Spider mite and predator densities were monitored twice a week. Spider mite densities were significantly affected by predator presence and light exposure. In the absence of predators, light exposure alone did not significantly influence spider mite densities. However, when predators were present, light regimes altered pest suppression dynamics. Under natural light and 12h LED exposure, predation effectively reduced spider mite densities over time. In contrast, continuous 24h LED exposure resulted in higher and more prolonged spider mite densities, suggesting that constant artificial lighting may disrupt predator efficiency and delay pest suppression. Predator densities also varied across light regimes, with continuous LED exposure leading to lower peak *N. californicus* densities than with 12h LED and natural light. Plant survival was unaffected by light in the absence of predators but was significantly lower under continuous light with predators than with natural light or 12-hour LED light, both with predators. These findings demonstrate that natural light and 12h LED conditions resulted in effective predator control of spider mites, whereas continuous LED exposure led to higher pest densities and lower predator efficiency, increasing the risk of pest outbreaks. These results highlight the need for careful management of artificial lighting in agricultural systems to ensure that LED use does not compromise biological control efficacy.

Keywords: *Tetranychus urticae*; *Neoseiulus californicus*; biological control; LED light.

RESUMO

SILVA, Rodrigo Cardoso, M.Sc., Universidade Federal de Viçosa, fevereiro de 2025. **Influência de diferentes condições de luz na dinâmica de *Tetranychus urticae* e no seu controle pelo ácaro predador *Neoseiulus californicus*.** Orientador: Arnoldus Rudolf Maria Janssen.

A crescente adoção da tecnologia LED na agricultura levanta questões ecológicas sobre seu impacto na dinâmica de pragas e inimigos naturais. Este estudo investiga os efeitos da exposição à luz LED na dinâmica populacional do ácaro-rajado (*Tetranychus urticae*) e seu controle pelo ácaro predador *Neoseiulus californicus*. Três tratamentos de luz foram aplicados: luz natural, 12 horas de luz LED com 12 horas de escuro e luz LED contínua por 24 horas. As densidades do ácaro-rajado e do predador foram monitoradas duas vezes por semana. As densidades do ácaro-rajado foram significativamente influenciadas pela presença do predador e pela exposição ao LED. Na ausência de predadores, a exposição ao LED por si só não afetou significativamente as populações do ácaro-rajado. No entanto, na presença de predadores, os regimes de luz alteraram a dinâmica de supressão da praga. Sob luz natural e exposição de 12 horas de LED, a predação reduziu efetivamente as densidades do ácaro-rajado ao longo do tempo. Em contraste, a exposição contínua de 24 horas de LED resultou em densidades mais altas e prolongadas do ácaro-rajado, sugerindo que a iluminação artificial constante pode prejudicar a eficiência do predador e atrasar a supressão da praga. As densidades de *N. californicus* também variaram entre os regimes de luz, sendo menores sob LED contínuo do que nos tratamentos de 12 horas de LED e luz natural. A sobrevivência das plantas não foi afetada pela luz na ausência de predadores, mas foi significativamente menor sob luz contínua com predadores do que nos tratamentos com luz natural ou 12 horas de LED, ambos com predadores. Esses resultados demonstram que as condições de luz natural e 12 horas de LED resultaram em um controle efetivo do ácaro-rajado pelos predadores, enquanto a exposição contínua ao LED levou a densidades mais altas da praga e menor eficiência do predador, aumentando o risco de surtos de pragas. Esses resultados destacam a necessidade de um manejo cuidadoso da iluminação artificial em sistemas agrícolas para garantir que o uso de LEDs não comprometa a eficácia do controle biológico.

Palavras-chave: *Tetranychus urticae*; *Neoseiulus californicus*; controle biológico; luz LED.

SUMMARY

<i>GENERAL INTRODUCTION</i>	8
<i>INTRODUCTION</i>	12
<i>MATERIALS AND METHODS</i>	14
REARING OF ORGANISMS.....	14
LED LIGHT EXPOSURE	14
COHORT PREPARATION AND INFESTATION	15
POPULATION DYNAMICS.....	16
STATISTICAL ANALYSIS	16
<i>RESULTS</i>	17
<i>DISCUSSION</i>	22
<i>GENERAL CONCLUSION</i>	25
<i>REFERENCES</i>	26

GENERAL INTRODUCTION

Biological control is a fundamental approach in sustainable agriculture, utilizing natural enemies to regulate pest populations. This approach has been used for over 2000 years, with a rich history of successes and challenges documented in the literature (DeBach 1964; Parra 2019; Fontes and Valadares-Inglis 2020). As a key component of integrated pest management (IPM) programs, biological control encompasses strategies based on the use of micro and macro-organisms, providing benefits such as reduced environmental impact and lower pesticide resistance (Ayaz et al. 2023; Manjunath 2023). However, its efficacy can be often influenced by factors such as environmental conditions, predator-prey interactions and the adaptability of biocontrol agents, necessitating ongoing research to optimize its application (Messing and Brodeur 2018).

Biological control strategies can be categorized into four types: natural, classical, augmentative, and conservation (Messing and Brodeur 2018). Natural biological control is an ecosystem service where pest organisms are reduced by naturally occurring beneficial organisms without any human intervention. For example, predatory insects like ladybugs and parasitic wasps naturally keep aphid densities in check (Scarpellini and Andrade 2011; Fines et al. 2024). Similarly, birds, spiders, and other predators help control insect populations in natural habitats (Van Lenteren et al. 2018). Classical biological control involves introducing natural enemies from a pest's native region to control its densities in a new environment. A well-known example is the introduction of the Vedalia beetle (*Rodolia cardinalis*) to control the cottony cushion scale (*Icerya purchasi*) in California citrus orchards in the late 19th century (Caltagirone and Doult 1989). The beetle, native to Australia, was introduced into California and successfully controlled the scale insect, saving the citrus industry. Augmentative biological control relies on the periodic release of commercially produced natural enemies to suppress pest populations (Hajek and Eilenberg 2018). An example is the release of *Trichogramma spp.* (parasitic wasps) to control lepidopteran pests in crops like corn, cotton, and vegetables. These wasps are mass-reared and released in large numbers to parasitize pest eggs (Fortes et al. 2023). In Brazil, *Trichogramma galloi* is one of the most widely used biological control agents, particularly for managing *Diatraea saccharalis* (sugarcane borer) in sugarcane plantations, due to its effectiveness, ease of mass production, and compatibility with integrated pest management strategies (Garcia et al. 2024). Conservation biological control focuses on modifying agricultural landscapes to support and enhance the

effectiveness of existing natural enemies (Hajek and Eilenberg 2018). For example, planting flower strips or hedgerows around agricultural fields provides nectar, pollen, and shelter for natural enemies like parasitic wasps, ladybugs, and hoverflies. These habitats enhance the survival and effectiveness of natural enemies, helping them control pests like aphids and caterpillars (Vargas et al. 2022).

Biological control relies on a diverse array of biocontrol agents, which can be divided into microbial and macrobial agents. Microbial biocontrol agents include pathogenic bacteria such as *Bacillus thuringiensis* (Bt) and fungi including *Beauveria bassiana*, but also viruses and nematodes. Macrobial biocontrol agents, such as lady beetles, parasitoid wasps and predatory mites, play a critical role in regulating pest densities in agricultural systems (Parra 2019). For example, the predatory mite *Neoseiulus californicus* is widely used as augmentative biocontrol agent to control phytophagous mites like *Tetranychus urticae*, making it valuable tool in IPM programs (Hajek and Eilenberg 2018; Vásquez et al. 2023).

Predators used for biological control are also classified into specialists and generalists, based on their feeding habits, but in reality, there is a continuum from extreme specialists to generalists. Specialist predators target a single prey species or a narrow group of closely related species and are often highly efficient in pest suppression (Akyazı and Liburd 2019). However, their reliance on specific prey makes them vulnerable to population declines if pest densities decrease. In contrast, generalist predators consume a wide variety of prey species, allowing them to adapt to fluctuations in prey availability, and persist even when certain prey are scarce. While this adaptability is advantageous, generalists may also consume non-target or beneficial species, potentially disrupting pest control (Stiling and Cornelissen 2005). *Neoseiulus californicus* is neither a generalist or a specialist predator; it preferentially feeds on *Tetranychus urticae* but can also consume other mite species, thrips, and pollen when primary prey is scarce (Akyazı and Liburd 2019).

The success of biological control does not only depend on the availability of suitable natural enemies, but is also influenced by environmental conditions such as temperature, humidity, and light availability (Hajek and Eilenberg 2018). As agricultural production systems increasingly incorporate new technologies to enhance efficiency and productivity, these advancements often result in environments that deviate significantly from natural ecosystems, particularly in controlled settings such as greenhouses (Paradiso and Proietti 2022; Decardi-Nelson and You 2024). Whereas greenhouses offer

advantages such as year-round production and protection from extreme weather, they also pose significant challenges for pest and natural enemy dynamics. The structural uniformity and consistent microclimate within greenhouses can unintentionally favor outbreaks of pests like mealybugs, thrips, and spider mites, which thrive under greenhouse conditions. Moreover, the frequent and often intensive use of chemical pesticides in these closed systems can cause rapid evolution of pesticide resistance, especially in pests with high reproductive rates (de Oliveira 1995).

Natural enemies and pests have evolved in complex and fluctuating environments characterized by natural light cycles, temperature fluctuations and plant diversity. When transferred to artificial environments, the effectiveness of pest regulation by the natural enemies may be compromised (Hougardy and Hogg 2022). Therefore, mass production of natural enemies in artificial environments can have negative effects on their size, fecundity, longevity, and fitness in general (Simmonds 1966; Boldt and Marston 1974; Lewis et al. 1976). It is therefore crucial to assess the compatibility of emerging technologies with biological control strategies to ensure their sustainability in integrated pest management programs.

One such technology gaining importance in modern agriculture is the use of LED lighting, which optimizes plant growth, extends growing seasons, and modifies plant physiological responses (Bantis et al. 2018; Budi et al. 2024). In Brazil, this technology is primarily applied to produce plant seedlings and during the initial stages of plant development, where precise control of environmental conditions is essential to ensure uniform germination, seedling vigor and overall quality. However, its impact on pest and natural enemy dynamics remains underexplored. Light influences arthropod behavior, reproduction, and foraging efficiency, potentially altering predator-prey interactions (Li et al. 2021). For example, spectral composition and photoperiod can affect the efficiency of natural enemies in controlling pests (Johansen et al. 2011; Shimoda and Honda 2013; Meijer et al. 2023). Park et al. (2022) found that 385 nm LED lighting improved *Nesidiocoris tenuis* control of *Bemisia tabaci* by attracting both predator and prey. (Park et al. 2022). This highlights that LED lighting can benefit biological control but its effects may vary across species and environmental conditions. Understanding these interactions is critical to ensuring that agricultural innovations like LED lighting do not compromise biological control effectiveness.

This dissertation examines the influence of LED lighting on the population dynamics of the two-spotted spider mite (*Tetranychus urticae*) and its natural enemy, the

predatory mite *Neoseiulus californicus*. The topic was chosen due to the increasing commercial use of *N. californicus* in biological control programs and the growing adoption of LED lighting in greenhouses as an energy-efficient alternative (Bantis et al. 2018; Messing and Brodeur 2018; Parra 2019; Paradiso and Proietti 2022). By evaluating different LED light regimes and their effects on predator-prey dynamics, this research provides insights into optimizing biological control strategies under artificial lighting conditions. The findings contribute to a broader understanding of how environmental modifications impact ecological processes in agricultural systems.

INTRODUCTION

Agricultural practices are rapidly evolving due to challenges such as the increase of the global human population, climate change and resource depletion (Maja and Ayano 2021; Fraser et al. 2024). Among the innovations shaping modern agriculture is the use of artificial light, especially Light Emitting Diodes (LED light) (Pode 2020; Budi et al. 2024). LED lights allow for precise control of plant growth conditions, resulting in applications in greenhouses, vertical farms, and urban agriculture where it enables year-round production regardless of external environmental factors (Naveen et al. 2024; Nhut and Nam 2010). Beyond optimizing plant growth, artificial lighting is utilized in agricultural settings to affect the breaking of seed dormancy, changing of the flowering period and extending shelf life (Paradiso and Proietti 2022). However, with the increase of LED usage in agricultural environments, concerns arise about how this form of lighting may influence the ecology and population dynamics of organisms in these ecosystems. In the specific context of biological pest control, it is essential to understand whether exposure to LED light affects the dynamics of pest organisms and their natural enemies.

The influence of artificial lighting on the behavior and physiology of arthropods is a growing area of research. Light can have profound effects on various biological processes and behavior of arthropods, including reproduction, feeding behavior, orientation and prey/predator interactions (Vänninen et al. 2010). Research shows that light, especially in the visible spectrum, can disrupt or enhance the development and reproductive behaviors of various arthropod species (Fabian et al. 2024). The spectral composition of LED lights can alter the behavioral responses of insects and mites by altering the visual cues they perceive, as their photoreceptors are finely tuned to detect different wavelengths (Suzuki et al. 2005; Van Grunsven et al. 2014; Pakyari and Zemek 2023). Different wavelengths such as red and far-red light can affect the growth and activity levels of pests such as spider mites (Meijer et al. 2023). Moreover, certain wavelengths of LED light have been shown to either inhibit or enhance oviposition rates in various insect and mite species, which is crucial for understanding population dynamics in pest control scenarios (Wang et al. 2013, 2020; Li et al. 2021).

As LED lighting becomes increasingly integrated into agricultural environments, its potential effects on pest and pathogen control warrant attention (Davis and Burns 2016). Successful biological control relies on the intricate balance of predator-prey interactions, which can be influenced by light conditions. The spectral composition of

LED light can alter the activity levels and distribution of pest species, such as *Tetranychus urticae*, potentially affecting their exposure to natural enemies (Meijer et al. 2023). Likewise, predators such as *Neoseiulus californicus* may experience changes in foraging efficiency, predation rates, and overall population dynamics under different lighting conditions (Yuan et al. 2020). Although researchers are increasingly investigating the ecological consequences of artificial light on predator-prey interactions (Johansen et al. 2011), the effects of LED light on predator-prey dynamics remain underexplored (Meijer et al. 2023). Given the importance of biological control in sustainable pest management, understanding how LED lighting influences these interactions is crucial. Here, I investigated the effects of LED light on a plant-inhabiting predator-pest system, focusing on *Tetranychus urticae* and *Neoseiulus californicus*.

Tetranychus urticae, the two-spotted spider mite, is a highly polyphagous and cosmopolitan pest that poses significant challenges in agriculture due to its high reproductive potential and rapid dispersal (Cazaux et al. 2014). *Neoseiulus californicus* is a well-known predator of *T. urticae*, and is widely used to control it (Gerson and Weintraub 2007). It is a predatory mite of the Phytoseiidae family, which are highly effective biocontrol agents due to their high fecundity and adaptability to diverse ecological conditions (Gulati 2014). *Neoseiulus californicus* is one of the most important commercially available predatory mites and plays a significant role in augmentative biological control (Vásquez et al. 2023). It is primarily used in protected vegetable and ornamental crop systems to control pests such as phytophagous mites, thrips, and whiteflies (Knapp et al. 2018). It is therefore critical to understand how artificial light conditions typical of modern agriculture affect the control of *T. urticae* by *N. californicus*. It is known that altering light conditions can influence the behavior of predatory mites, potentially affecting their ability to suppress pest populations (Tachi and Osakabe 2012; Meijer et al. 2023). With their customizable spectral outputs, LED lights offer an opportunity to manipulate the behavior of both pests and predators, making it essential to assess how lighting conditions influence the population dynamics of plant pests and their natural enemies. The current study is exactly on this topic. By quantifying the dynamics of *T. urticae* and *N. californicus* under different lighting conditions, this study contributes to the development of more effective biological control and integrated pest management strategies.

MATERIALS AND METHODS

REARING OF ORGANISMS

Individuals used in the experiment were obtained from the existing rearing unit of the Department of Entomology, Federal University of Viçosa (UFV) MG, Brazil. Individuals of the two-spotted spider mite (*Tetranychus urticae*) were collected from velvet bean (*Canavalia ensiformis*, host plants, cultivated under greenhouse conditions. Individuals of the predator *N. californicus* were collected from the rearing room at the Acarology Laboratory. Collection was done with fine brushes and Petri dishes for safe transportation of the individuals to the laboratory. The collected mites were maintained under controlled conditions: temperature ($25 \pm 2^\circ\text{C}$), relative humidity (60-70%), and photoperiod (12 hours of light and 12 hours of darkness). These standardized conditions helped to ensure control over environmental variables that could influence the development and behavior of the mites and their predators. The host plants used to maintain mite and predator populations were velvet bean (*Canavalia ensiformis*), cultivated in pots under the same environmental conditions.

On May 17, three velvet bean seeds were planted per pot (top $\varnothing = 17\text{cm}$; base = 11.8cm ; 13cm high), with a total of 50 pots all filled with substrate based on pine bark (Mecplant). The plants were housed in rectangular cages ($0.45 \times 0.50 \times 1.00\text{m}$) with transparent mesh to prevent contamination. These cages were placed on an external balcony at the Department of Animal Biology at UFV, exposed to ambient conditions.

LED LIGHT EXPOSURE

To assess the effects of LED light exposure, three different lighting regimes were established: Natural Light plus 12h LED: a combination of ambient natural light supplemented with LED light from 6 am to 6 pm, as used in most greenhouse systems. Natural Light plus 24h LED: a combination of ambient natural light supplemented with continuous LED light for 24 hours. Natural: exposure to ambient natural light without artificial supplementation.

The supplemental lighting consisted of 50W full spectrum LED panels, emitting light with a spectral distribution confirmed with a Horiba spectrofluorimeter. The measured emission ranged from 360 to 800 nm, covering the entire photosynthetically active radiation spectrum (400–700 nm) as well as adjacent UV-A and far-red

wavelengths. The spectrum showed major intensity peaks in the blue (430–470 nm) and red (620–680 nm) regions, consistent with plant growth requirements, and had appreciable intensity across the full spectrum, qualifying as broad-spectrum illumination. Each panel delivered approximately 6000 lumens with a consumption of 50 W/h, and featured a 120° beam angle, low heat emission (passive dissipation), and high energy efficiency. Panels were mounted at a standardized 0.8m height on the top of the experimental cages to ensure consistent irradiance across all replicates. These lighting treatments were applied to experimental cages containing plants infested with *T. urticae* and their predators *N. californicus*.

COHORT PREPARATION AND INFESTATION

To standardize the age of mites used in the experiment, cohorts were obtained for both *T. urticae* and *N. californicus* by placing 500 adult females of *T. urticae* on a clean velvet bean leaf. The following day, all adult females were removed, eggs were allowed to develop into adults, clean leaves were added once as fresh food source, and mites were used for the experiment 10 days later.

Similarly, a cohort of *N. californicus* was obtained using 150 adult females placed on velvet bean leaves containing *T. urticae* as a food source. These leaves were placed in 7.5 L white plastic trays, which were placed inside a larger tray of the same material filled with a mixture of water and detergent. The smaller trays were suspended on top of rectangles sponges at the height of the solution to prevent contamination and escapes. The following day, all adult females were removed, and eggs were allowed to develop into adults, with additional *T. urticae*-infested leaves added twice as a food supplement until mites were used eight days later. The trays with leaves were maintained in rearing rooms at $25 \pm 2^\circ\text{C}$, 60 - 70% relative humidity and a photoperiod of 12 hours light and 12 hours dark.

On June 6, 2024, velvet bean plants with the two first true leaves (each in a separate pot) were placed into the experimental cages. Each cage contained three plants that did not touch each other, thus preventing movement of mites between plants. There were two cages per treatment, hence, a total of six plants (replicates) per treatment. On the same day, 15 adult females of *T. urticae* were taken from the cohort and introduced onto the bean plants. On June 13, 2024, the cages were subjected to their respective LED light treatments (natural light only, 12h of LED plus natural light, 24h of LED plus natural

light), and three adult females of *N. californicus* were added to each plant on two cages of each light treatment, resulting in six treatments in total (3 light treatments, either with or without predators).

POPULATION DYNAMICS

Population dynamics of two-spotted spider mites and predatory mites were monitored twice per week from June 20 to August 5, 2024) by counting the adult female spider mites and predatory mites using hand lenses and tally counters. To facilitate counting, only the two true leaves of each plant were used for observations, and newly emerging trifoliolate leaves were removed as they appeared.

STATISTICAL ANALYSIS

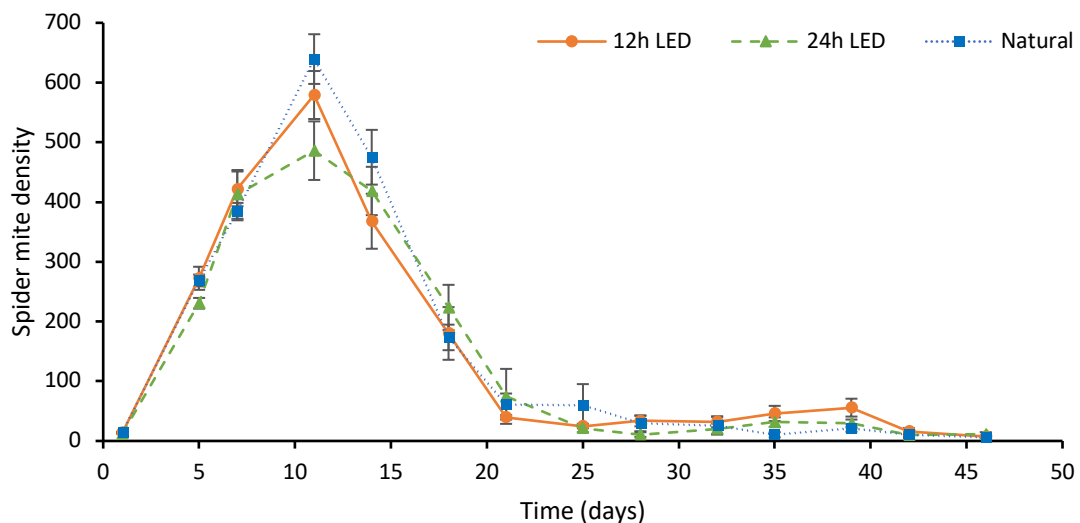
Numbers of mites were $\ln(x+1)$ transformed and analyzed using a linear mixed-effects model (LME). Plant identity was included as a random effect to account for repeated measures within each plant. Light treatments were considered fixed effects. Light treatment (12h LED, 24h LED, Natural), predator presence (yes/no), and time, including polynomial terms (time^2 and time^3 to account for non-linearity in mite dynamics), were included as fixed effects. Interactions between light and predator presence, as well as between each time factor and light/predator factors were also included. Models were selected and simplified using likelihood ratio (L.R.) tests and the Akaike Information Criterion (AIC) to determine the most parsimonious model. Model diagnostics were performed to assess goodness-of-fit and ensure that model assumptions were met. If significant differences among treatments were detected, pairwise post hoc comparisons were conducted by aggregating treatment levels.

A similar modeling approach was applied to analyze the density of *N. californicus*, considering light, time, time^2 and time^3 , and spider mite densities as fixed effects, and including a random intercept for individual plants. Plant survival was assessed using a Cox proportional hazards analysis with log-rank test to compare survival curves and aggregation of treatments to identify significant differences between treatments. The number of leaves of surviving plants was analyzed with a generalized linear model (GLM) with a Poisson error distribution, with light, predator presence, and the cumulative numbers of spider mites per plant as fixed effects. Data were analyzed using R software version 4.0.0 (R Project for Statistical Computing. <http://www.r-project.org>).

RESULTS

Spider mite densities varied significantly through time, with light regimes and with the presence or absence of predators (Fig. 1, lme, interaction of light, predators and time: L.R. = 12.38, d.f. = 2, $p = 0.021$). The dynamics of the mites was non-linear (lme, interaction of light regime with time²: L.R. = 6.57, d.f. = 2, $p = 0.037$, interaction of light with time³: L.R. = 7.03, d.f. = 2, $p = 0.030$). Without predators, peak densities of spider mites were much higher than with predators (Fig. 1), 12h LED: interaction of predator presence/absence with time: L.R. = 14.0, d.f. = 1, $p = 0.0002$; 24h LED: interaction of predator presence with time: L.R. = 4.60, d.f. = 1, $p = 0.032$, with time²: L.R. = 13.0, d.f. = 1, $p = 0.0003$, with time³: L.R. = 15.6, d.f. = 1, $p = 0.0001$; natural light: interaction of predator presence with time: L.R. = 6.96, d.f. = 1, $p = 0.008$, with time²: L.R. = 12.4, d.f. = 1, $p = 0.0004$, with time³: L.R. = 12.5, d.f. = 1, $p = 0.0004$). Furthermore, the light regime had no significant effect on spider mite densities when predators were absent (Fig. 1a, lme: L.R. = 1.97, d.f. = 2, $p = 0.37$). In contrast, the light regime affected spider mite densities significantly through time when predators were present (Fig. 1b, lme, interaction of light with time: L.R. = 28.1, d.f. = 2, $p < 0.0001$), with the overall pest densities with natural light being the lowest and those with 24h of LED light the highest (Fig. 1b).

a. Without predators



b. With predators

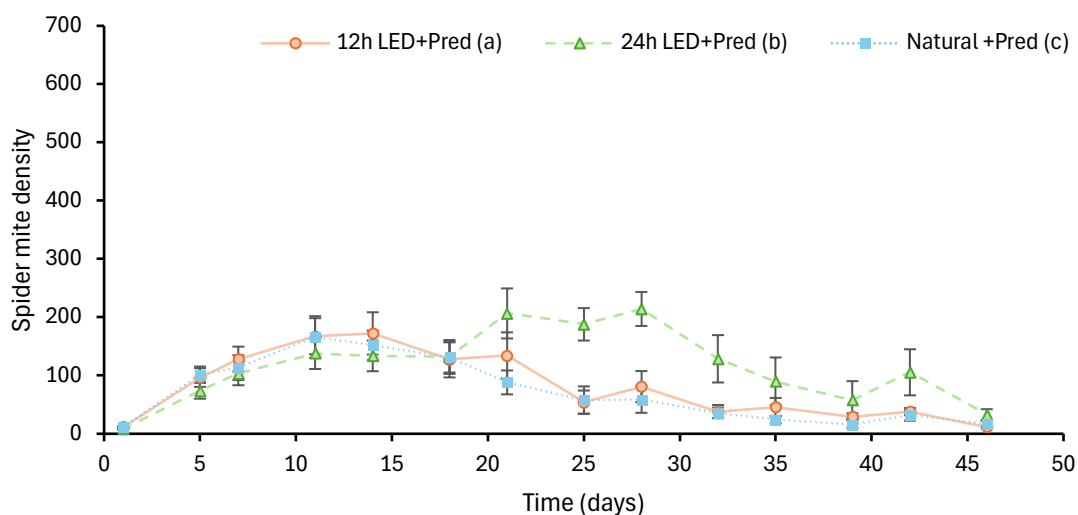


Figure 1. Spider mite (*Tetranychus urticae*) densities over time in the absence (a) and in the presence of predators (b) under different light regimes. Treatments included 12h LED (solid line), 24h LED (dashed line), Natural light (dotted line). Points represent mean spider mite densities, with error bars indicating standard errors. Letters in the legend in (b) show significance among light conditions (contrasts after lme).

Predator densities varied significantly over time and with light regimes and with spider mite density (Fig. 2, lme, interaction of light, spider mite densities and time²: L.R. = 10.4, d.f. = 2, p = 0.0056). Predator numbers with 24h of LED light differed significantly from the other two treatments through time, reaching lower maximum densities (Fig. 2). Owing to these lower densities, pest densities with continuous LED light became higher than with natural light or with 12h of LED light (Fig. 1a, 3).

Predators

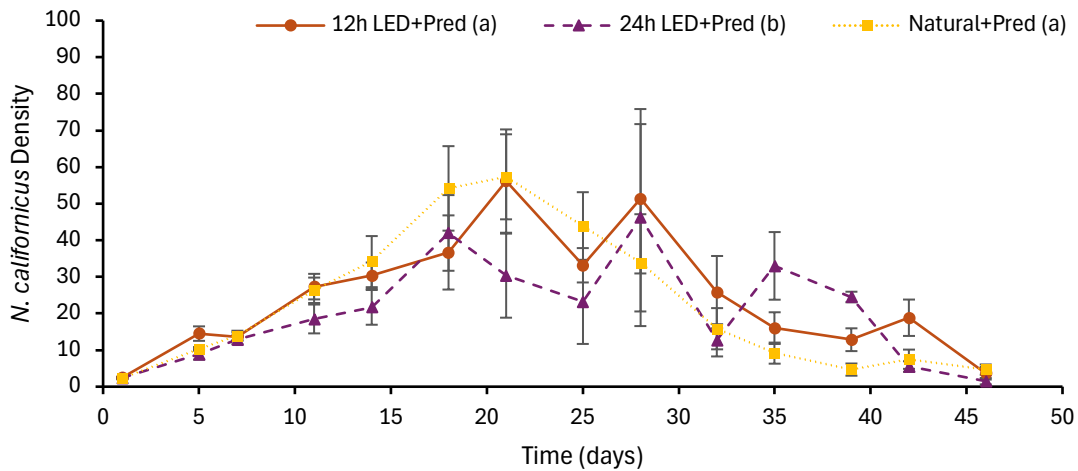


Figure 2. *Neoseiulus californicus* densities over time under different light regimes: 12 h LED (solid line), 24h LED (dashed line), and natural light (dotted line). Points represent mean predatory mite densities, with error bars indicating standard error. Letters in the legend in (b) show significance among light conditions (contrasts after lme).

Predator-prey dynamics varied over time across all light conditions (Fig. 3) with predation effects becoming more pronounced over time. Under natural light, *T. urticae* densities increased rapidly during the first 12-15 days, reaching a peak, and then declined as predator densities increased. Under 12h LED, a similar pattern was observed, but the prey population remained slightly higher for longer, showing a slower decline after peaking. Finally, under 24h LED, *T. urticae* densities remained elevated for a prolonged period, fluctuating between days 20-35, suggesting reduced predator efficiency. Although *N. californicus* densities increased, they remained lower than in the other two light treatments, leading to delayed pest suppression. These results suggest that continuous LED exposure may have altered predator foraging efficiency, delaying the reduction of prey population compared to natural and 12h LED treatments.

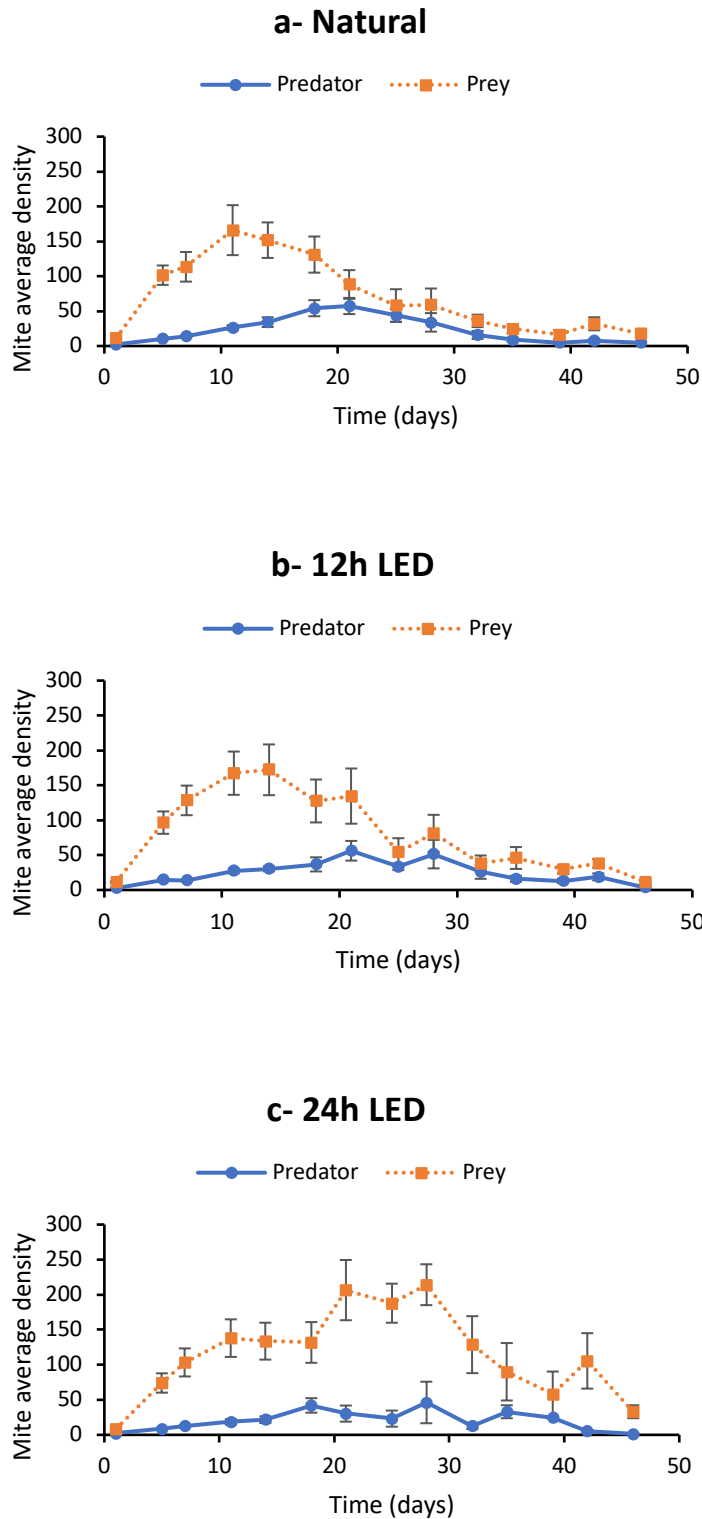


Figure 3. Predator-prey dynamics of *Neoseiulus californicus* and *Tetranychus urticae* under different light regimes: Natural light (a), 12h LED (b), and 24h LED (c). Predator densities (solid blue line) and prey densities (dashed orange line) are shown over time. Points represent mean mite densities, with error bars indicating standard errors.

Overall, there was a significant difference in plant survival among light regimes (Fig. 4, Cox proportional hazards: L.R. = 15.7, d.f. = 5, $p = 0.008$). All plants with predators receiving natural light or 12h LED light survived, but plants with predators receiving 24h LED light had the lowest survival (Fig. 4).

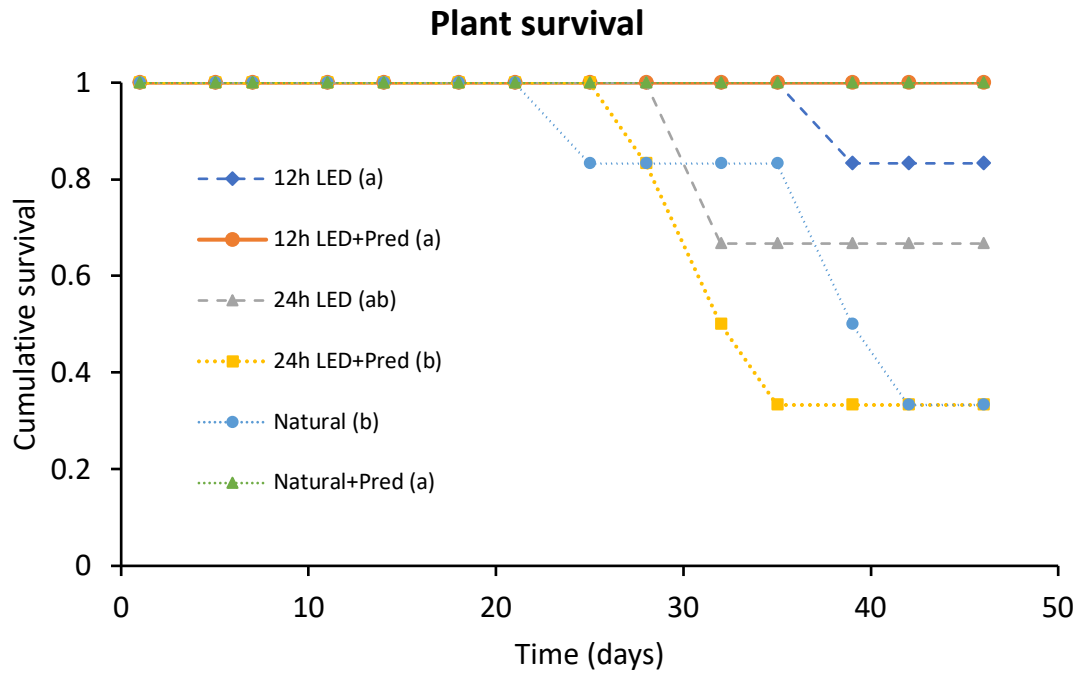


Figure 4. Plant survival over time under different light regimes and predator presence or absence. Treatments included 12h LED (dashed blue line), 12h LED+Pred (solid orange line), 24h LED (dashed gray line), 24h LED+Pred (dotted yellow line), Natural light (dotted black line), and Natural+Pred (dotted green line). Points represent cumulative survival, with different line styles indicating treatment conditions.

An analysis of the final numbers of leaves of those plants that survived until the end of the experiment showed no significant effects of light conditions, presence/absence of predators or the total numbers of spider mites on the plants or of their interactions (Fig. 5. $p > 0.05$ for all factors and interactions). Hence, the number of leaves of surviving plants were relatively similar regardless of the experimental treatments.

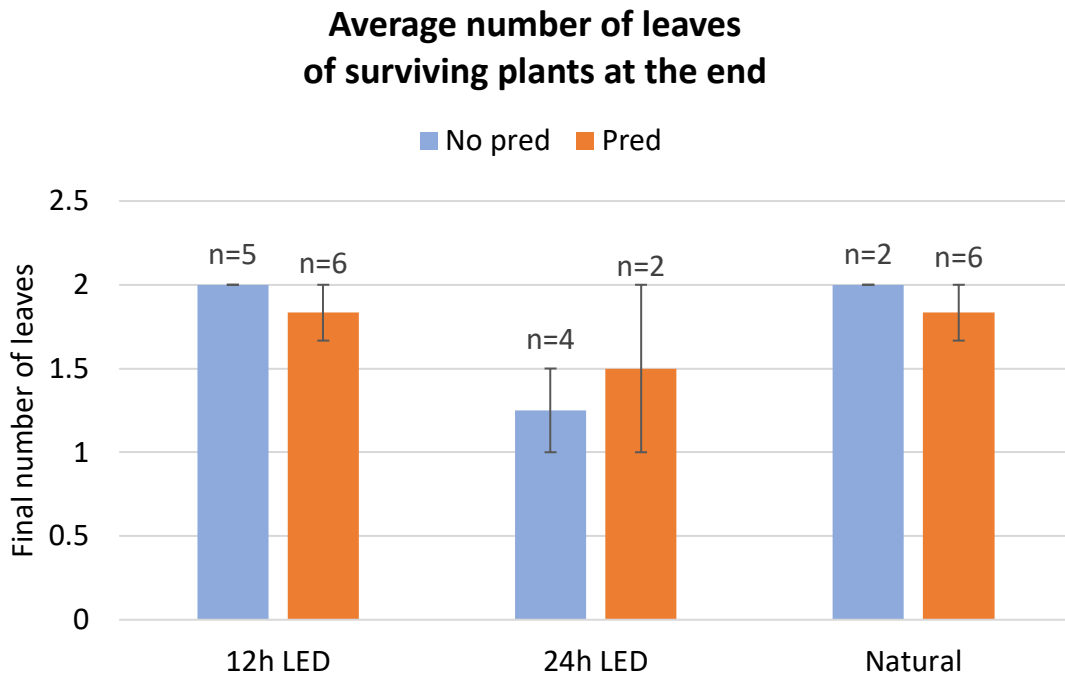


Figure 5. Average numbers of leaves of surviving plants at the end of the experiment under different light regimes (12h LED, 24h LED, and Natural) and predator presence (Pred) or absence (No pred). Bars represent mean final leaf number out of maximum 2 leaves, with error bars indicating standard errors. The sample size (number of surviving plants) is indicated by n. Colors indicate predator treatments. No significant differences were found among treatments ($p > 0.05$).

DISCUSSION

Our study demonstrates that LED lighting influences the population dynamics of *Tetranychus urticae* and *Neoseiulus californicus*, with continuous exposure to LED light (24h) leading to significantly higher spider mite densities. Predator presence strongly impacted *T. urticae* densities, but under continuous LED lighting, the suppression effect of *N. californicus* was delayed and reduced, allowing pest populations to remain elevated for longer periods before declining. Additionally, plant survival differed significantly among treatments, particularly in the presence of predators. Under 24h LED conditions, plants in predator treatments had lower survival rates than those under 12h LED and natural light conditions. However, the number of leaves among the surviving plants did not differ significantly across treatments, suggesting that while light and predation

influenced plant mortality, the vigor of surviving plants was not strongly affected. It should be noted, though, that spider mite damage of the leaves was not quantified. These findings are important in the context of modern agricultural practices, as artificial lighting is increasingly used to optimize plant growth in controlled environments (Vänninen et al. 2010; Singh et al. 2015; Bantis et al. 2018).

While artificial lighting offers many benefits for plant production, our results highlight potential challenges in pest management. These findings are consistent with Kruidhof (2023), who pointed out that light can influence biological control both directly, by affecting predator behavior, and indirectly, through plant-mediated effects (Kruidhof 2023). The lower efficiency of *N. californicus* under continuous LED exposure may be partially explained by such mechanisms.

Our findings contribute to the growing body of research on the effects of artificial light on arthropod interactions and biological control. For instance, Meijer et al. (2023) discovered that supplemental far-red light modified herbivore-induced volatile organic compound emissions by tomato plants without disrupting predator attraction. Although both *Tetranychus urticae* and *P. persimilis* populations increased under far-red light, the overall suppression of *T. urticae* remained comparable to control conditions, indicating that biological control was not disrupted. In contrast, our study, conducted over a longer observation period and under continuous LED exposure (24h), showed a reduction in the efficiency of *Neoseiulus californicus* and a delay in the suppression of *T. urticae* densities. These results suggest that artificial lighting can negatively impact biological control, and that the effects of light on predator–prey dynamics may depend on factors such as light duration, spectral composition, and predator species.

Similarly, Vänninen et al. (2010) demonstrated that artificial lighting in high-tech greenhouse environments influenced arthropods, primarily through plant-mediated effects. Factors such as extended photoperiods, reduced UV exposure, altered red:far-red and blue:red ratios, and seasonal changes in light quality were found to impact herbivore performance (Vänninen et al. 2010). These results align with our results, as the delayed suppression on *T. urticae* under continuous LED exposure may be partially driven by plant-mediated changes. While emerging LED technologies offer opportunities to manipulate plant responses to light, our study highlights that not all artificial light conditions enhance biological control. Specifically, continuous LED exposure may hinder the effectiveness of *N. californicus* in controlling *T. urticae* and should be avoided in integrated pest management strategies.

Additionally, Tachi and Osakabe (2012) showed that altered light conditions can impact predation rates and dispersal behavior by altering the predators' perception of the environment and increasing their light avoidance behavior. Consistently, our results show that *N. californicus* densities under 24h LED exposure were significantly lower and reached lower peak densities compared to the 12h LED and natural light treatments. This may be a consequence of disrupted circadian rhythms or altered activity cycles, ultimately reducing predation of *T. urticae*. Moreover, predator densities varied significantly over time, with light regimes influencing their population dynamics.

Despite lacking eyes, *N. californicus* has been shown to detect and respond to harmful light, particularly ultraviolet-B (UVB) radiation (Tachi and Osakabe 2014). Phytoseiid mites, including *N. californicus*, are more vulnerable to UVB than spider mites, which may influence their foraging and dispersal behavior. Laboratory studies have demonstrated that *N. californicus* females actively escape from UV radiation, with quicker responses to shorter, more harmful wavelengths (Tachi and Osakabe 2014). This ability to detect and respond to different light wavelengths, despite being blind, indicates that *N. californicus* relies on non-visual photoreceptors to regulate its behavior. Along with olfactory stimuli, this ability helps explain how *Neoseiulus californicus* locates its prey (Sakai and Osakabe 2010). Although we did not measure the wavelengths our findings suggest that continuous LED exposure (24h) led to lower predator densities and reduced peak levels compared to 12h LED or natural light. While UV radiation triggers immediate escape, prolonged LED exposure may disrupt activity cycles, likely affecting foraging and reproduction.

Our study provides a key insight that LED lighting can influence predator-prey interactions in an agricultural context, particularly in greenhouses systems, where LED lighting is extensively used (Bantis et al. 2018). However, several questions remain unanswered, warranting further investigation. Future research should focus on uncovering the precise mechanisms by which continuous LED exposure affects the foraging efficiency, reproductive behavior, and overall fitness of the predatory mites. Additionally, environmental factors such as humidity, temperature fluctuations, and plant volatiles may play a role in mediating these light-induced changes and should be further explored.

It is crucial to assess the broader implications of using artificial lighting for the functioning of all biological control agents used under artificial conditions, including predatory insects and parasitoids, to determine whether similar disruptions occur across

different natural enemy guilds. As LED technology continues to expand in modern farming, understanding its ecological consequences is essential for developing integrated pest management strategies that optimize both plant growth and pest control efficacy.

GENERAL CONCLUSION

With the rapid technification of agricultural systems, innovations such as LED lighting are increasingly integrated into crop productions to enhance efficiency and sustainability (Vänninen et al. 2010). This study highlights the impact of LED lighting on predator-prey interactions, specifically the population dynamics of *Tetranychus urticae* and *Neoseiulus californicus*. The results demonstrate that continuous LED exposure (24h) significantly alters pest suppression, leading to higher spider mite densities and reduced plant survival compared to natural and 12-hour LED light conditions. These findings underscore the necessity of considering artificial lighting effects when implementing biological control strategies in controlled agricultural environments.

Biological control is an essential sustainable strategy of pest management, offering an eco-friendly alternative to chemical pesticides. However, as agricultural practices develop with the integration of advanced technologies such as LED lighting, it is crucial to understand how these innovations influence pest – natural enemy dynamics. The observed reduction in *N. californicus* efficacy under continuous LED exposure suggests that light-mediated behavioral and physiological changes may impact the success of biocontrol programs.

A key aspect that requires further investigation is how *N. californicus*, a species with limited vision, responds to continuous LED exposure. As a primarily tactile predator that relies on mechano- and chemoreception to locate prey, altered light conditions may interfere with its ability to navigate, forage efficiently, and regulate its activity cycles. Understanding how different light exposure durations and intensities affect the physiological and behavioral adaptations of *N. californicus* will be crucial for improving biological control strategies in artificial environments. Moreover, since *N. californicus* is a species known to feed on alternative food sources, it is important to explore whether artificial light influences its feeding behavior, including its preference for different types such as spider mites and other arthropods and food items like pollen. Identifying whether shifts in feeding behavior occur under different lighting conditions could provide insights

into how best to deploy this predator in integrated pest management programs where artificial lighting is used.

In conclusion, while LED lighting presents opportunities for improving agricultural efficiency, its influence on natural enemies and biocontrol must be carefully studied and managed. By integrating species-specific knowledge with technological advancements, sustainable agricultural systems can be developed that enhance both crop production and sustainable agriculture. Further research focusing on the physiology, behavior, and reproductive performance of *N. californicus* and other natural enemies under different lighting regimes will be instrumental in optimizing LED-based pest management strategies in controlled agricultural systems.

REFERENCES

Akyazi R, Liburd OE (2019) Biological control of the two-spotted spider mite (Trombidiformes: Tetranychidae) with the predatory mite *Neoseiulus californicus* (Mesotigmata: Phytoseiidae) in blackberries. *Fla Entomol* 102:373–381. <https://doi.org/10.1653/024.102.0217>

Ayaz M, Li C, Gao X, et al (2023) Bacterial and fungal biocontrol agents for plant disease protection: journey from lab to field, current status, challenges, and global perspectives. *Molecules* 28:6735. <https://doi.org/10.3390/molecules28186735>

Bantis F, Smirnakou S, Ouzounis T, et al (2018) Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). *Sci Hortic* 235:437–451. <https://doi.org/10.1016/j.scienta.2018.02.058>

Boldt PE, Marston N (1974) Eggs of the greater wax moth as a host for *Trichogramma*. *Environ Entomol* 3:545–548. <https://doi.org/10.1093/ee/3.3.545>

Budi P, Regia PA, Andy S (2024) The effect of light emitting diode (LED) spectrum and light duration on growth and yield of *Brassica sinensis* L. grown on floating raft hydroponic system. *BIO Web Conf* 90:02002. <https://doi.org/10.1051/bioconf/20249002002>

Caltagirone LE, Douth RL (1989) The history of the Vedalia beetle importation to California and its impact on the development of biological control. *Annu Rev Entomol* 34:1–16. <https://doi.org/10.1146/annurev.en.34.010189.000245>

Cazaux M, Navarro M, Bruinsma KA, et al (2014) Application of two-spotted spider mite *Tetranychus urticae* for plant-pest interaction studies. *J Vis Exp* e51738. <https://doi.org/10.3791/51738>

Davis PA, Burns CO (2016) Photobiology in protected horticulture. *Food Energy Secur* 5:223–238. <https://doi.org/10.1002/fes3.97>

de Oliveira MRV (1995) O emprego de casas de vegetação no Brasil: vantagens e desvantagens. *Pesqui Agropecuária Bras* 30:1049–1060. <https://doi.org/10.1590/S1678-3921.pab1995.v30.4396>

DeBach P (1964) Some ecological aspects of insect eradication. *Bull Entomol Soc Am* 10:221–224. <https://doi.org/10.1093/besa/10.4.221>

Decardi-Nelson B, You F (2024) Artificial intelligence can regulate light and climate systems to reduce energy use in plant factories and support sustainable food production. *Nat Food* 5:869–881. <https://doi.org/10.1038/s43016-024-01045-3>

Fabian ST, Sondhi Y, Allen PE, et al (2024) Why flying insects gather at artificial light. *Nat Commun* 15:689. <https://doi.org/10.1038/s41467-024-44785-3>

Fines B, Roel AR, Pentead-Dias A (2024) Insetos parasitoides nativos no controle biológico de pragas como base para agricultura sustentável. *Rev DELOS* 17:e2337. <https://doi.org/10.55905/rdelosv17.n60-109>

Fontes EMG, Valadares-Inglis MC (2020) Controle biológico de pragas da agricultura. Embrapa, Brasília, DF

Fortes A dos R, Coelho AAD, Amorim DJ, et al (2023) Biology and quality assessment of *Telenomus remus* (Hymenoptera: Scelionidae) and *Trichogramma spp.* (Hymenoptera: Trichogrammatidae) in eggs of *Spodoptera spp.* for augmentative biological control programs. *J Insect Sci* 23:5. <https://doi.org/10.1093/jisesa/iead047>

Fraser JL, Abram PK, Dorais M (2024) Supplemental LED lighting improves plant growth without impeding biological control of aphids with parasitoids in a tri-trophic greenhouse system. *J Pest Sci* 97:1343–1354. <https://doi.org/10.1007/s10340-023-01703-8>

Garcia AG, Wajnberg E, Parra JRP (2024) Optimizing the releasing strategy used for the biological control of the sugarcane borer *Diatraea saccharalis* by *Trichogramma galloi* with computer modeling and simulation. *Sci Rep* 14:9535. <https://doi.org/10.1038/s41598-024-60146-y>

Gerson U, Weintraub PG (2007) Mites for the control of pests in protected cultivation. *Pest Manag Sci* 63:658–676. <https://doi.org/10.1002/ps.1380>

Gulati R (2014) Eco-friendly management of phytophagous mites. In: Abrol DP (ed) *Integrated Pest Management*. Academic Press, San Diego, pp 461–491

Hajek AE, Eilenberg J (2018) *Natural enemies: An introduction to biological control*, 2nd edn. Cambridge University Press, Cambridge, UK

Hougardy E, Hogg BN (2022) Factors affecting progeny production and sex ratio of *Gryon aetherium* (Hymenoptera: Scelionidae), a candidate biological control agent for

Bagrada hilaris (Hemiptera: Pentatomidae). Insects 13:1010.
<https://doi.org/10.3390/insects13111010>

Johansen NS, Vänninen I, Pinto DM, et al (2011) In the light of new greenhouse technologies: 2. Direct effects of artificial lighting on arthropods and integrated pest management in greenhouse crops. *Ann Appl Biol* 159:1–27.
<https://doi.org/10.1111/j.1744-7348.2011.00483.x>

Knapp M, van Houten Y, van Baal E, Groot T (2018) Use of predatory mites in commercial biocontrol: current status and future prospects. *Acarologia* 58:72–82.
<https://doi.org/10.24349/acarologia/20184275>

Kruidhof M (2023) Direct effects of (LED) light on arthropod behaviour and biological pest control. *IOBC-WPRS Bull* 167:84–91

Lewis WJ, Nordlund DA, Gross HR Jr, et al (1976) Production and performance of *Trichogramma* reared on eggs of *Heliothis zea* and other hosts. *Environ Entomol* 5:449–452. <https://doi.org/10.1093/ee/5.3.449>

Li W, Quan L, Dong Y, et al (2021) Effects of white LED light on reproduction of *Conopomorpha sinensis* (Lepidoptera: Gracillariidae) and its field application. *J Fruit Sci* 38:1349–1358. <https://doi.org/10.13925/j.cnki.gsxb.20210182>

Maja MM, Ayano SF (2021) The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. *Earth Syst Environ* 5:271–283. <https://doi.org/10.1007/s41748-021-00209-6>

Manjunath TM (2023) Integration of augmentative biocontrol with synthetic pesticides and other control methods for IPM – Challenges and prospects*. *J Biol Control* 36:179–186. <https://doi.org/10.18311/jbc/2022/34091>

Meijer D, van der Vleut J, Weldegergis BT, et al (2023) Effects of far-red light on tritrophic interactions between the two-spotted spider mite (*Tetranychus urticae*) and the predatory mite *Phytoseiulus persimilis* on tomato. *Pest Manag Sci* 79:1820–1828.
<https://doi.org/10.1002/ps.7358>

Messing RH, Brodeur J (2018) Current challenges to the implementation of classical biological control. *Biocontrol* 63:1–9. <https://doi.org/10.1007/s10526-017-9862-4>

Naveen, Singh G, Saha P, et al (2024) Enhancing plant growth: Harnessing the effectiveness of artificial light. *J Adv Biol Biotechnol* 27:59–72.
<https://doi.org/10.9734/jabb/2024/v27i4739>

Nhut DT, Nam NB (2010) Light-Emitting Diodes (LEDs): An artificial lighting source for biological studies. In: Van Toi V, Khoa TQD (eds) *The Third International Conference on the Development of Biomedical Engineering in Vietnam*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 134–139

Pakaryi H, Zemek R (2023) Effects of visible light wavelength on development

and demographic parameters of *Phytoseiulus persimilis* (Acari: Phytoseiidae). Syst Appl Acarol 28:1843–1854. <https://doi.org/10.11158/saa.28.12.2>

Paradiso R, Proietti S (2022) Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. J Plant Growth Regul 41:742–780. <https://doi.org/10.1007/s00344-021-10337-y>

Park Y, Lee J-H, Lim UT (2022) Use of UV-LED light to enhance establishment of *Nesidiocoris tenuis* for control of *Bemisia tabaci* infesting greenhouse tomato. Biol Control 170:104936. <https://doi.org/10.1016/j.biocontrol.2022.104936>

Parra JRP (2019) Controle biológico na agricultura brasileira. Entomological Communications 1:ec01002. <https://doi.org/10.37486/2675-1305.ec01002>

Pode R (2020) Organic light emitting diode devices: An energy efficient solid state lighting for applications. Renew Sustain Energy Rev 133:110043. <https://doi.org/10.1016/j.rser.2020.110043>

Sakai Y, Osakabe M (2010) Spectrum-specific Damage and Solar Ultraviolet Radiation Avoidance in the Two-spotted Spider Mite. Photochem Photobiol 86:925–932. <https://doi.org/10.1111/j.1751-1097.2010.00739.x>

Scarpellini JR, Andrade DJ de (2011) Efeito de inseticidas sobre a joaninha *Cycloneda sanguinea* L. (Coleoptera, Coccinellidae) e sobre o pulgão *Aphis gossypii* Glover (hemiptera, aphididae) em algodoeiro. Arq Inst Biológico 78:393–399. <https://doi.org/10.1590/1808-1657v78p3932011>

Shimoda M, Honda K (2013) Insect reactions to light and its applications to pest management. Appl Entomol Zool 48:413–421. <https://doi.org/10.1007/s13355-013-0219-x>

Simmonds JF (1966) Insect colonization and mass production. In: Insect parasites and predators. Academic Press, New York, pp 489–499

Singh D, Singh DK, Singh D, et al (2015) LEDs for energy efficient greenhouse lighting. Renew Sustain Energy Rev 49:139–147. <https://doi.org/10.1016/j.rser.2015.04.117>

Stiling P, Cornelissen T (2005) What makes a successful biocontrol agent? A meta-analysis of biological control agent performance. Biol Control 34:236–246. <https://doi.org/10.1016/j.biocontrol.2005.02.017>

Suzuki T, Amano H, Kozai T (2005) Effect of visible light wavelengths on the population growth rate of the two-spotted spider mite (*Tetranychus urticae* Koch.). Hortscience 40:1025B – 1025. <https://doi.org/10.21273/hortsci.40.4.1025b>

Tachi F, Osakabe M (2012) Vulnerability and behavioral response to ultraviolet radiation in the components of a foliar mite prey–predator system. Naturwissenschaften 99:1031–1038. <https://doi.org/10.1007/s00114-012-0984-3>

Tachi F, Osakabe M (2014) Spectrum-specific UV egg damage and dispersal responses in the Phytoseiid predatory mite *Neoseiulus californicus* (Acari: Phytoseiidae). *Environ Entomol* 43:787–794. <https://doi.org/10.1603/en13336>

Van Grunsven RHA, Donners M, Boeke K, et al (2014) Spectral composition of light sources and insect phototaxis, with an evaluation of existing spectral response models. *J Insect Conserv* 18:225–231. <https://doi.org/10.1007/s10841-014-9633-9>

Van Lenteren JC, Bolckmans K, Köhl J, et al (2018) Biological control using invertebrates and microorganisms: plenty of new opportunities. *BioControl* 63:39–59. <https://doi.org/10.1007/s10526-017-9801-4>

Vänninen I, Pinto DM, Nissinen AI, et al (2010) In the light of new greenhouse technologies: 1. Plant-mediated effects of artificial lighting on arthropods and tritrophic interactions. *Ann Appl Biol* 157:393–414. <https://doi.org/10.1111/j.1744-7348.2010.00438.x>

Vargas G, Vargas G, Rivera-Pedroza LF, et al (2022) Conservation biological control as an important tool in the neotropical region. *Neotrop Entomol* 52:134–151. <https://doi.org/10.1007/s13744-022-01005-1>

Vásquez C, Colmenárez YC, Greco N, Ramos M (2023) Current status of Phytoseiid mites as biological control agents in Latin America and experiences from Argentina using *Neoseiulus californicus*. *Neotrop Entomol* 52:240–250. <https://doi.org/10.1007/s13744-023-01026-4>

Wang F-Y, Li L-F, Wei Q-X, et al (2020) Effects of different light environments on oviposition of *Conopomorpha sinensis* and its control efficacy in field. *J South Agric* 51:313–318. <https://doi.org/10.3969/j.issn.2095-1191.2020.02.009>

Wang S, Tan XL, Michaud JP, et al (2013) Light intensity and wavelength influence development, reproduction and locomotor activity in the predatory flower bug *Orius sauteri*(Poppius) (Hemiptera: Anthocoridae). *BioControl* 58:667–674. <https://doi.org/10.1007/s10526-013-9522-2>

Yuan L, Mori S, Haruyama N, et al (2020) Strawberry pollen as a source of UV - B protection ingredients for the phytoseiid mite *Neoseiulus californicus* (Acari: Phytoseiidae). *Pest Manag Sci* 77:851–859. <https://doi.org/10.1002/ps.6089>