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Low-Intensity White Light Optimises Development, Reproduction, and Predation of *Cryptolaemus montrouzieri* on *Dactylopius opuntiae*: Implications for Mass Rearing and Biological Control

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ABSTRACT

Cryptolaemus montrouzieri (Mulsant) is an important predator of *Dactylopius opuntiae* (Cockerell) and widely used in biological control programs. This study assessed the effects of light color (white, blue, and yellow) and intensity (230–690 lux) on the development, survival, and reproduction of *C. montrouzieri* under laboratory conditions ($25 \pm 1^\circ\text{C}$, $66 \pm 5\%$ RH, 16:8 h light:dark). Pre-adult developmental times were shortest under white (230–350 lux) (35.0 days for females, 34.4–34.5 days for males) and longest under blue-690 lux (females (56.3 days), males (55.6 days)). Pre-adult survival was highest under white-230 lux (0.8) and lowest under yellow-690 lux (0.3), with the highest female proportion (0.4) under white-230 lux. Adult longevity ranged from 92.2 days (white-690 lux) to 197.9 days (blue-690 lux) for females and from 91.2 days (white-690 lux) to 196.4 days (blue-460 lux) for males. Fecundity peaked under white-230 lux (221.4 eggs/female) and was lowest under yellow-690 lux (81.9 eggs/female). Population growth parameters were maximal under white-230 lux (intrinsic rate $r = 0.049\text{ d}^{-1}$; net reproductive rate $R_0 = 87.4$ offspring/female). Predation was highest under white-230 lux (8,926 eggs, 8,739 first-instar nymphs, 7,405 second-instar nymphs, and 349 adult females per individual). Morphometric traits and body weight were highest under white light-230 lux, with adults measuring $5.7 \times 3.4\text{ mm}$ and fourth-instar larvae measuring $8.6 \times 3.9\text{ mm}$; body weight was likewise highest under white-230 lux for adults (5.7 mg) and fourth-instar larvae (3.7 mg), compared to 5.3 mg and 3.4 mg, respectively, under blue-690 lux. Overall, low-intensity white light (230–350 lux) optimizes development, survival, reproduction, and predation efficiency of *C. montrouzieri*, supporting improved mass-rearing and biological control applications.

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1. Introduction

Among the abiotic factors shaping arthropod physiology, behavior, and ecology, light is one of the most influential [1-3]. Its photoperiod, intensity, and spectral quality shift with daily and seasonal cycles, and insects use these variations as cues that regulate development, reproduction, activity, foraging, and food intake [3].

The role of photoperiod in insect development and reproduction is well characterized. Several beetle species develop faster under extended daylight [4-6], whereas moths tend to emerge from the pupal stage preferentially during long dark periods, illustrating how photoperiodic responses differ among taxa [7, 8]. Within the Coccinellidae, long-day white-light regimes (approximately 16:8 h light:dark) increase mating frequency and shorten mating bouts in the aphid-feeding ladybird *Coelophora saucia* (Mulsant), pointing to a stimulatory effect of extended photoperiods on reproductive behavior [9]. A comparable pattern occurs in the predatory ladybird *Cheilomenes sexmaculata* (Fabricius), which develops faster and oviposits more under 14–16 h of daily light, reinforcing the general importance of photoperiod for life-history traits [10]. The moth *Heliothis virescens* (Fabricius) (Lepidoptera: Noctuidae), by contrast, emerges preferentially during prolonged darkness [7].

Beyond photoperiod, light intensity and colour markedly affect insect movement and foraging. Raising illuminance from 1000 to 5000 lux nearly doubled locomotor activity in the anthocorid predator *Orius sauteri* (Poppus) (Heteroptera: Anthocoridae), and within this species walking speed was fastest under red light, intermediate under yellow, and slowest under white, green, or blue light [11]. In the ladybird *Hippodamia variegata* (Goeze), a combination of extended photoperiods (0:24–24:0 L:D), elevated intensities (0.6–1.8 W m⁻²), and blue, green, or purple wavelengths shortened immature development to 13.6–18.8 days, compressed mating and pre-oviposition intervals (12.1–6.9 days; 203.5–65.8 min), and extended both the oviposition period (15.4–22.7 days) and lifetime fecundity (96.2–149.6 eggs/female) [8, 12, 13]. A similar hierarchy of light preference appears in *Cheilomenes sexmaculata* (Fabricius) and *Propylea dissecta* (Mulsant), which develop fastest, reproduce most, and reach the highest fitness under white light (195 ± 5 lux), with yellow, blue, and red light progressively less favourable [3]. Spectral quality also shapes feeding: ultraviolet and blue wavelengths suppress feeding in the hoverfly *Eristalis tenax* (L.) (Diptera: Syrphidae) and the hawkmoth *Manduca sexta* (L.) (Lepidoptera: Sphingidae), and ultraviolet light additionally lowers mating activity in *Drosophila melanogaster* Meigen [14, 15], whereas red and white light instead promote locomotion and predation across a range of predatory taxa, underscoring how behavioural responses are wavelength-specific [3, 11]. Colour vision in ladybirds is well documented and shapes both prey recognition and foraging efficiency [16, 17], and predation by *C. sexmaculata* and *P. dissecta* peaks under white or red light at moderate intensity (roughly 150–300 lux) and long photoperiods (about 14–16 h), while ultraviolet or blue light suppresses activity in these species [18-20].

Photoperiod and light intensity also act at a physiological level, governing diapause timing and developmental scheduling. In ladybirds, extended photoperiods combined with moderate illuminance favour continued development and reproduction, whereas shorter days and dim conditions can trigger diapause [21, 22]; the duration, intensity, and colour of light likewise feed directly into predatory behaviour, as shown for *H. variegata*, *C. sexmaculata*, *Harmonia axyridis* (Pallas), and other coccinellid predators [3, 23].

Native to Australia, *Cryptolaemus montrouzieri* (Coleoptera: Coccinellidae) owes its common name, the mealybug destroyer, to the voracious feeding of both larvae and adults on mealybugs [24]. This predatory efficiency has led to its introduction across numerous countries as a biological control agent against a range of mealybug species, establishing it as an important natural enemy in many agricultural systems [25-27]. Among its targets is the cactus false cochineal, *Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae), against which *C. montrouzieri* has been deployed in several countries [27, 28], with mixed field success: laboratory trials in Brazil were promising, yet field performance declined under heavy infestation and elevated temperature [28]; releases in Israel did not halt the spread of *D. opuntiae* [29], although they significantly suppressed coastal populations [27]; and in Morocco, releasing 30 adults per square metre reduced the pest population by 92% within 77 days, a result that has also prompted follow-up trials in Tunisia [30]. Within the predator's life cycle, adults and fourth-instar larvae consume *D. opuntiae* most voraciously [31]. As in other coccinellids, vision plays a central role in how *C. montrouzieri* locates prey, recognizes mates, and selects oviposition sites [32, 33], which suggests its performance

could be sensitive to the ambient light environment; nonetheless, the photoperiod, intensity, and wavelength conditions best suited to this species have not been thoroughly investigated.

Clarifying how light affects *C. montrouzieri* therefore has direct practical value: it could inform more efficient mass-rearing protocols, help the predator adapt to varying release environments, and ultimately strengthen its contribution to integrated pest management. Adjusting the light regime used in rearing — for instance, by favouring longer photoperiods (14–16 h), moderate intensities (150–300 lux), and spectral qualities such as white or red light — might accelerate development, improve survival, boost reproduction, and sharpen predatory behaviour, benefits that would carry over into greenhouse or field releases where lighting conditions vary widely. Against this background, the present study examines how photoperiod, intensity, and light colour shape the life history, reproduction, and predatory performance of *C. montrouzieri* feeding on *D. opuntiae*, with the aim of identifying light conditions that improve mass-rearing efficiency, predator performance, and the sustainability of biological control against cactus cochineal.

2. Materials and Methods

2.1. Insect Rearing

The colony of *C. montrouzieri* was established from adults obtained by the Entomology Laboratory at the insectarium of the National Institute of Agricultural Research (INRA) in Zemamra, Morocco (32°37'48" N, 8°42'0" W; 165 m a.s.l.). Adults were maintained in transparent entomological cages (50 × 50 × 50 cm) covered with mesh fabric to ensure proper ventilation. A moistened cotton ball in a Petri dish (14.5 cm diameter) served as a water source. Cladodes of *Opuntia ficus-indica* (L.) Miller (Caryophyllales: Cactaceae) infested with *D. opuntiae* were placed in the cages to provide both a substrate for oviposition and a food source for *C. montrouzieri*. Infested cladodes were added as needed, and any cladode showing the start of rot was removed to maintain colony health. To prevent competition and cannibalism between larvae and adults, larvae were transferred to separate cages of the same size to complete their development. The cochineal colony was initiated from infected *O. ficus-indica* collected in Zemamra, and the population was expanded and age-monitored following the protocol of Aldama-Aguilera and Llanderal-Cázares [34]. Mature cladodes were standardized by cutting, pierced at their base with a wooden stake, left to heal for 48 h, and then suspended vertically on metal grids inside the cages. Both *C. montrouzieri* and *D. opuntiae* colonies were maintained under controlled conditions at 25 ± 1 °C, $66 \pm 5\%$ RH, 16:8 h light:dark photoperiod, and 400 lux white light intensity. Ladybird adults obtained after two generations under laboratory conditions were used in the experiments.

2.2. Development, Survival, and Reproduction Studies

The experiment to assess the development, survival and reproduction of *C. montrouzieri* feeding on *D. opuntiae* was conducted under controlled laboratory conditions in rearing rooms measuring 7 × 5 × 3 m. Environmental conditions were maintained at 25 ± 1 °C, $66 \pm 5\%$ relative humidity, and a 16:8 h light:dark photoperiod. Light treatments consisted of three colors (white, blue, and yellow) provided by 65 W lamps of identical make, wattage, and fixture type, differing only in the colour of the bulb/filter used (Philips Lighting, Signify, Netherlands), so that colour was not confounded with lamp hardware. Four light intensities were obtained by varying the number of lamps (one to five per room), corresponding approximately to 230, 350, 460, and 690 lux, measured at the container level using a digital lux meter (Extech Instruments, model EA33, USA); because adding discrete lamp units produces a non-linear, additive increase in measured illuminance rather than evenly spaced steps, the resulting four intensity levels were not equally spaced, and intensity was accordingly treated as a categorical rather than continuous factor in all analyses. Each room was assigned a single combination of light color and intensity for the duration of a complete insect life cycle. Once a treatment was completed, rooms were sequentially reassigned to the next combination until all treatments were tested; because each treatment occupied its assigned room for the full duration of a life cycle before the next treatment began, room and time (cohort sequence) are not statistically separable from treatment in this design, and any room-specific or seasonal drift in temperature, humidity, or light homogeneity would be confounded with the treatment effect. Treatments were not assigned to rooms at random and rooms were not modelled as a blocking or random-effect factor, and no formal test for carry-over effects between successive treatments in the same room was conducted; this is

acknowledged as a limitation of the design (Section 6). To obtain a cohort of eggs of uniform age, 40-paired adults of *C. montrouzieri* from the laboratory colony were placed individually in plastic Petri dishes (14.5 cm diameter) containing different stages of *D. opuntiae*. Eggs laid within 24 h were collected with a fine camel-hair brush (No. 000) and transferred individually to smaller Petri dishes (9.5 cm diameter) lined with white filter paper. Eggs were pooled across the 40 paired females assigned to each light treatment, and the resulting cohort sizes (number of eggs/individuals tracked at each stage) for every treatment are reported in parentheses in Table 1. Each egg was considered a replicate, and incubation period and hatching percentage (fertility) were recorded. After hatching, larvae and adults were provided daily with an excess of *D. opuntiae* throughout development. Survival and developmental duration of larval instars, prepupae, and pupae were recorded daily. Upon adult emergence, males and females (0–24 h old) were paired in 14.5 cm plastic Petri dishes. If a male died before the female, a newly emerged male was introduced. Adult longevity and fecundity (number of eggs laid per female) were recorded daily until all individuals died. Each female was individually monitored to document the total pre-oviposition period (TPOP) — from egg to sexually mature adult — along with the oviposition and post-oviposition (from last egg laying to death) phases. Female longevity was calculated as the sum of these reproductive stages. The sex ratio of offspring was determined following Seyfollahi *et al.* (2016) [35]. To monitor offspring development, approximately 90 first-instar larvae were randomly collected from 20-mated females ten days after the start of oviposition and allowed to develop under the same light treatment. All trials were replicated twice at different times to ensure consistency and reliability of the results.

2.3. Predation Efficiency

In a separate experiment, the predation efficiency of *C. montrouzieri* was studied using free-choice feeding tests. Forty-five newly emerged first-instar larvae (<one day old) were isolated individually in Petri dishes (14.5 cm diameter) and provided daily with 10 eggs, 15 first-instar nymphs, 10 second-instar nymphs, and 5 adult females of *D. opuntiae*. Second-instar larvae were provided daily with 40 eggs, 45 first-instar nymphs, 35 second-instar nymphs, or 15 adult females per Petri dish. Fourth-instar larvae and adult beetles were provided daily with 100 eggs, 105 first-instar nymphs, 75 second-instar nymphs, and 20 adult females per Petri dish. Observations of prey consumption were recorded daily for each individual from the first-instar stage until the death of the adult beetles. Individual weights of larvae and adults were measured 24 h after molting using a precise electronic balance (OHAUS CORPORATION, USA) accurate to 0.001 mg. The experiment was independently repeated twice over time.

2.4. Data Analysis

In this study, we evaluated the development, survival, reproduction, and predation of *C. montrouzieri* on *D. opuntiae* under 12 different light treatments combining color and intensity (lux): white (230, 350, 460, 690), yellow (230, 350, 460, 690), and blue (230, 350, 460, 690). All experiments were conducted at 25 ± 1 °C, $66 \pm 5\%$ relative humidity, and a 16:8 h light:dark photoperiod.

The life table and population growth parameters of *C. montrouzieri* were calculated using the age-stage, two-sex life table method [36, 37] with the TWOSEX-MSChart software [38]. The net reproductive rate (R_0) represents the total number of offspring produced per female during her lifetime and was calculated as:

$$R_0 = \sum_{x=0}^{\infty} I_x m_x$$

where I_x is the age-specific survival rate and m_x is the age-specific fecundity.

The intrinsic rate of increase (r) represents the population growth rate under ideal conditions and was estimated using the Euler–Lotka equation, with age indexed from 0 [39]:

$$\sum_{x=0}^{\infty} e^{-r(x+1)} I_x m_x = 1$$

The mean generation time (T), which is the average time between two successive generations, was calculated as:

$$T = \frac{\ln R_0}{r}$$

The gross reproductive rate (GRR), or the total number of female offspring produced by a female during her lifetime, was calculated as:

$$GRR = \sum_{x=\alpha}^{\infty} m_x$$

The finite rate of increase (λ), representing population growth over discrete time periods, was calculated as:

$$\lambda = e^r$$

Table 1: Mean ($\pm$ SEM) developmental time and pre-adult survival of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments combining color and intensity (lux).

Statistic Parameters	Treatments (Color-Intensity (Lux))											
	White-230	White-350	White-460	White-690	Yellow-230	Yellow-350	Yellow-460	Yellow-690	Blue-230	Blue-350	Blue-460	Blue-690
Developmental Time (Days)												
Egg	3.4 d $\pm 0.1(186)$	3.6 c $\pm 0.1(171)$	3.7 c $\pm 0.1(163)$	4.9 b $\pm 0.1(157)$	5.2 a $\pm 0.1(133)$	5.2 a $\pm 0.1(129)$	5.2 a $\pm 0.1(125)$	5.4 a $\pm 0.1(119)$	5.1 b $\pm 0.1(151)$	5.3 a $\pm 0.1(146)$	5.4 a $\pm 0.1(142)$	5.6 a $\pm 0.1(138)$
Larvae	20.6 d $\pm 0.2(171)$	20.4 e $\pm 0.2(153)$	21.3 c $\pm 0.2(138)$	29.7 c $\pm 0.2(129)$	30.4 b $\pm 0.3(109)$	30.7 b $\pm 0.3(107)$	31.8 b $\pm 0.3(103)$	32.6 a $\pm 0.3(97)$	32.7 a $\pm 0.2(125)$	33.4 a $\pm 1.9(120)$	34.4 a $\pm 0.1(116)$	35.4 a $\pm 0.1(112)$
Pupa	10.7 c $\pm 0.1(171)$	10.8 c $\pm 0.1(153)$	10.8 c $\pm 0.1(138)$	13.7 b $\pm 0.1(129)$	13.6 b $\pm 0.1(109)$	13.7 b $\pm 0.1(107)$	14.1 a $\pm 0.1(103)$	14.3 a $\pm 0.1(97)$	14.3 a $\pm 0.1(125)$	14.5 a $\pm 0.1(120)$	14.9 a $\pm 0.1(116)$	15.1 a $\pm 0.1(105)$
Preadult female	35.0 dA $\pm 0.3(79)$	35.0 cA $\pm 0.2(68)$	36.1 cA $\pm 0.3(59)$	48.7 bA $\pm 0.4(56)$	49.0 bA $\pm 0.5(41)$	49.4 bA $\pm 0.6(40)$	51.9 aA $\pm 0.5(38)$	53.4 aA $\pm 0.3(34)$	52.4 aA $\pm 0.5(53)$	53.8 aA $\pm 0.3(50)$	55.1 aA $\pm 0.2(47)$	56.3 aA $\pm 0.3(44)$
Preadult male	34.5 cA $\pm 0.3(76)$	34.4 dA $\pm 0.2(64)$	35.7 cA $\pm 0.3(54)$	48.2 bA $\pm 0.4(52)$	48.3 bA $\pm 0.5(40)$	49.5 aA $\pm 0.5(38)$	51.2 aA $\pm 0.4(36)$	53.0 aA $\pm 0.3(33)$	52.1 aA $\pm 0.5(50)$	53.2 aA $\pm 0.4(48)$	54.6 aA $\pm 0.3(45)$	55.6 aA $\pm 0.2(42)$
Female longevity	172.8 cA $\pm 0.6(79)$	172.5 cA $\pm 0.5(68)$	174.6 bA $\pm 0.6(59)$	92.2 dA $\pm 0.8(56)$	186.3 abA $\pm 1.1(41)$	187.6 aA $\pm 1.0(40)$	190.0 aA $\pm 1.0(38)$	192.0 aA $\pm 0.6(34)$	195.7 aA $\pm 1.0(53)$	196.2 aA $\pm 0.7(50)$	197.9 aA $\pm 0.1(47)$	197.9 aA $\pm 0.5(44)$
Male longevity	171.5 cA $\pm 0.5(76)$	171.2 cA $\pm 0.5(64)$	173.7 cA $\pm 0.7(54)$	91.2 dA $\pm 0.8(52)$	185.0 bcA $\pm 1.1(40)$	185.7 bA $\pm 1.2(38)$	188.5 abA $\pm 1.0(36)$	191.0 abA $\pm 0.6(33)$	194.3 abA $\pm 1.1(50)$	194.6 abA $\pm 0.8(48)$	196.4 aA $\pm 0.8(45)$	196.3 aA $\pm 0.6(42)$
Female proportion in cohort (N _f /N)	0.4 a ± 0.03	0.3 a ± 0.03	0.3 ab ± 0.03	0.3 ab ± 0.03	0.2 bc ± 0.03	0.2 bc ± 0.03	0.2 c ± 0.03	0.2 c ± 0.03	0.3 ab ± 0.03	0.3 ab ± 0.03	0.2 c ± 0.03	0.2 c ± 0.03
Preadult mortality	0.2 d ± 0.03	0.3 d ± 0.03	0.4 c ± 0.04	0.5 b ± 0.04	0.6 b ± 0.03	0.6 ab ± 0.03	0.6 ab ± 0.03	0.7 a ± 0.03	0.5 c ± 0.04	0.5 c ± 0.04	0.5 b ± 0.04	0.6 a ± 0.04
Preadult survival (Sa)	0.8 a ± 0.03	0.7 b ± 0.03	0.6 bc ± 0.04	0.5 c ± 0.04	0.4 d ± 0.03	0.4 de ± 0.03	0.4 e ± 0.03	0.3 f ± 0.03	0.5 bc ± 0.04	0.5 c ± 0.04	0.5 cd ± 0.04	0.4 e ± 0.04

Values within parentheses are sample sizes.

Values in rows followed by the same small letter are not significantly different using the paired bootstrap test at 5% significance level.

Values in columns followed by the same capital letter are not significantly different using the paired bootstrap test at 5% significance level.

Additional parameters included age-stage specific fecundity (f_{xj}), age-specific fertility (m_x), and age-specific maternity ($l_x m_x$), preadult survival rates, and sex ratio (proportion of females). Sample sizes varied among treatments and developmental stages because of stage-specific mortality. Initial egg numbers ranged from 119 to 186 individuals per treatment, with the numbers reaching subsequent developmental stages reported in Table 1. Variances and standard errors of all life table, reproduction, and population growth parameters were estimated using bootstrap techniques with 100,000 resamplings for each parameter and treatment [40]. Significant differences among treatments were determined using a paired bootstrap test in TWSEX-MSChart [38]. With 12 treatments, each parameter involved 66 possible pairwise comparisons ($12 \times 11 / 2$). Across the life-table, reproductive, and population-growth parameters reported in Table 1-3, several hundred pairwise comparisons were therefore conducted in total. Pairwise comparisons were performed using the paired bootstrap procedure

implemented in TWSEX-MSChart [38], and no additional correction for multiple comparisons (e.g., false discovery rate or Bonferroni adjustment) was applied. Accordingly, the letter-based groupings in Table 1-3 should be interpreted within the paired-bootstrap comparison framework used by TWSEX-MSChart rather than as results adjusted for family-wise or false-discovery error rates.

Table 2: Mean ($\pm$ SEM) pre-oviposition, oviposition, post-oviposition periods, fecundity, daily reproduction (eggs $\times$ female⁻¹ $\times$ day⁻¹), and egg mortality of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments combining color and intensity (lux).

Treatments (Color-Intensity (Lux))	Total Pre-oviposition Period (Days)	Oviposition Period (Days)	Post-oviposition Period (Days)	Fecundity (Eggs/Female)	Daily Fecundity (Eggs $\times$ Female ⁻¹ $\times$ Day ⁻¹)	Eggs Mortality
White-230	70.1 $\pm$ 0.5 B	51.6 $\pm$ 0.3 AB	48.6 $\pm$ 0.3 A	221.4 $\pm$ 1.8 A	4.1 $\pm$ 0.03 A	0.1 $\pm$ 0.02 G
White-350	69.9 $\pm$ 0.5 B	54.2 $\pm$ 0.2 A	45.8 $\pm$ 0.4 AB	185.3 $\pm$ 1.5 B	3.3 $\pm$ 0.03 B	0.2 $\pm$ 0.03 F
White-460	72.2 $\pm$ 0.6 B	68.8 $\pm$ 0.5 A	29.5 $\pm$ 0.6 C	110.3 $\pm$ 2.0 C	1.5 $\pm$ 0.03 F	0.2 $\pm$ 0.03 F
White-690	97.4 $\pm$ 0.8 AB	69.6 $\pm$ 2.6 A	18.9 $\pm$ 0.6 E	92.9 $\pm$ 0.8 CD	1.2 $\pm$ 0.02 H	0.2 $\pm$ 0.03 E
Yellow-230	98.0 $\pm$ 1.0 A	48.2 $\pm$ 0.2 AB	37.3 $\pm$ 0.5 B	93.5 $\pm$ 0.9 C	1.8 $\pm$ 0.02 E	0.3 $\pm$ 0.03 C
Yellow-350	99.4 $\pm$ 0.9 A	50.0 $\pm$ 0.2 AB	37.3 $\pm$ 0.3 B	96.3 $\pm$ 1.0 C	1.9 $\pm$ 0.02 D	0.4 $\pm$ 0.03 B
Yellow-460	103.7 $\pm$ 0.9A	51.1 $\pm$ 0.4 AB	30.0 $\pm$ 0.5 C	88.3 $\pm$ 0.9 D	1.6 $\pm$ 0.02 F	0.4 $\pm$ 0.03 A
Yellow-690	106.8 $\pm$ 0.6A	54.2 $\pm$ 0.2 A	25.3 $\pm$ 0.3 D	81.9 $\pm$ 0.6 D	1.4 $\pm$ 0.01 G	0.4 $\pm$ 0.03 A
Blue-230	104.9 $\pm$ 0.9A	44.8 $\pm$ 0.2 B	43.4 $\pm$ 0.7 AB	107.8 $\pm$ 1.1 C	2.3 $\pm$ 0.03 C	0.2 $\pm$ 0.03 D
Blue-350	107.5 $\pm$ 0.6A	45.0 $\pm$ 0.3 B	40.5 $\pm$ 0.6 B	107.5 $\pm$ 1.0 C	2.2 $\pm$ 0.02 C	0.3 $\pm$ 0.03 D
Blue-460	110.2 $\pm$ 0.5A	47.8 $\pm$ 0.2 B	36.1 $\pm$ 0.5 B	105.3 $\pm$ 0.8 C	2.0 $\pm$ 0.02 D	0.3 $\pm$ 0.03 C
Blue-690	112.5 $\pm$ 0.4A	48.3 $\pm$ 0.4 AB	33.9 $\pm$ 0.4 C	99.6 $\pm$ 1.0 C	1.9 $\pm$ 0.03 D	0.3 $\pm$ 0.03 B

Values in columns followed by the same capital letter are not significantly different using the paired bootstrap test at 5% significance level.

Table 3: Mean ($\pm$ SEM) population growth parameters of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments combining color and intensity (lux).

Treatments (Color- Intensity (Lux))	Parameters:				
	r (Days ⁻¹)	λ (Days ⁻¹)	R_0 (Offspring)	GRR (Eggs per Female)	T (Days)
White-230	0.049 $\pm$ 0.001 A	1.050 $\pm$ 0.001 A	87.4 $\pm$ 7.7 A	91.0 $\pm$ 0.5 A	112.5 $\pm$ 8.9 E
White-350	0.045 $\pm$ 0.001A	1.046 $\pm$ 0.001 A	63.0 $\pm$ 6.2 A	94.6 $\pm$ 8.1 A	92.7 $\pm$ 0.5 E
White-460	0.034 $\pm$ 0.001 A	1.035 $\pm$ 0.001 A	32.5 $\pm$ 3.6 B	57.3 $\pm$ 5.2 B	100.7 $\pm$ 0.7 E
White-690	0.025 $\pm$ 0.001 B	1.026 $\pm$ 0.001 B	26.0 $\pm$ 3.0 B	47.9 $\pm$ 4.5 B	129.1 $\pm$ 0.9 C
Yellow-230	0.024 $\pm$ 0.001 B	1.025 $\pm$ 0.001 B	19.2 $\pm$ 2.7 C	45.8 $\pm$ 5.1 B	121.2 $\pm$ 1.0 D
Yellow-350	0.024 $\pm$ 0.001 B	1.024 $\pm$ 0.001 B	19.3 $\pm$ 2.7 C	48.3 $\pm$ 5.4 B	122.6 $\pm$ 1.0 D
Yellow-460	0.022 $\pm$ 0.001 C	1.022 $\pm$ 0.001 C	16.8 $\pm$ 2.5 C	44.5 $\pm$ 5.1 B	127.2 $\pm$ 1.0 C
Yellow-690	0.020 $\pm$ 0.001 C	1.020 $\pm$ 0.001 C	13.9 $\pm$ 2.2 C	41.4 $\pm$ 5.0 C	133.5 $\pm$ 0.6 B
Blue-230	0.027 $\pm$ 0.001 A	1.027 $\pm$ 0.001 A	28.6 $\pm$ 3.4 B	55.0 $\pm$ 5.3 B	126.2 $\pm$ 1.1 C
Blue-350	0.025 $\pm$ 0.001 B	1.026 $\pm$ 0.001 B	26.9 $\pm$ 3.3 B	54.5 $\pm$ 5.4 B	129.4 $\pm$ 0.7 C
Blue-460	0.024 $\pm$ 0.001 B	1.024 $\pm$ 0.001 B	24.7 $\pm$ 3.2 B	53.6 $\pm$ 5.5 B	133.1 $\pm$ 0.6 B
Blue-690	0.023 $\pm$ 0.001 C	1.023 $\pm$ 0.001 C	21.9 $\pm$ 2.9 B	50.5 $\pm$ 5.3 B	135.4 $\pm$ 0.5 A

The standard errors were calculated using the bootstrap procedure with 100000 bootstraps.

Values in columns followed by the same small letter are not significantly different using the paired bootstrap test at 5% significance level.

The effects of the tested treatments on the predatory performance of ladybirds (number of *D. opuntiae* individuals consumed by different stages of *C. montrouzieri*) as well as on their morphometric measurements and weight were analyzed using Tukey's LSD test ($p = 0.05$) in IBM SPSS Statistics version 23.0. This analytical approach allowed for a comprehensive evaluation of survival, reproduction, predation efficiency, and population growth of *C. montrouzieri* under the tested environmental and light conditions.

3. Results

3.1. Developmental Time, and Pre-adult Survival of *C. montrouzieri* Under Different Light Treatments

Developmental times of different life stages of *C. montrouzieri* fed on *D. opuntiae* were significantly affected by light color and intensity (Table 1; $P < 0.05$). Egg development varied across light treatments, with the shortest mean duration recorded under white-230 lux (3.4 days) and the longest under Blue-690 lux (5.6 days). The total pre-adult developmental time of females ranged from 35.0 days (white-350 lux and white-230 lux) to 56.3 days (blue-690 lux), and for males from 34.5 days to 55.6 days, showing a clear prolongation of development under higher light intensities and specific colors. Female and male adult longevities were also significantly influenced by light treatments. Females lived from 172.5 days (white-350 lux) up to 197.9 days (blue-690 lux), while males ranged from 171.2 ± 0.5 to 196.4 ± 0.8 days. Notably, longevities were shorter under intermediate white-690 lux conditions (females: 92.2 days; males: 91.2 days). The proportion of females in the cohort (N_f/N) ranged from 0.2 to 0.4 depending on light treatment, with the highest female proportion observed under white-230 lux and white-350 lux (0.4 and 0.3 respectively) and the lowest under blue-460 lux and Blue-690 (0.2). Pre-adult mortality ($1 - S_a$) also varied with light conditions, ranging from 0.2 under white-230 lux to 0.7 under yellow-690 lux, resulting in pre-adult survival (S_a) values from 0.3 to 0.8. Overall, white light at lower intensities (230–350 lux) produced the shortest developmental times, higher pre-adult survival, and higher female proportions, suggesting optimal conditions for rapid development and population growth of *C. montrouzieri*. In contrast, higher intensities of blue and yellow light delayed development, reduced survival, and lowered female proportions, indicating less favorable conditions for development and reproduction.

3.2. Reproduction Parameters

The age-specific survival rate curve (l_x) shows changes in survival of the whole cohort of *C. montrouzieri* with increasing age under different light treatments. This parameter is strongly influenced by light color and intensity, with the highest survival observed under blue-690 lux and the lowest under white-690 lux conditions. In contrast, under optimal white light intensities (white-230 and White-350), females reached reproductive maturity earlier, resulting in a higher proportion of time spent laying eggs. The highest peaks for age-stage fecundity ($f(x, \text{female})$), age-specific fertility (m_x), and age-specific maternity ($l_x m_x$) were recorded under white-230 and white-350 lux, indicating that individuals under these conditions are more reproductive and pre-adult survival is higher compared to those under high-intensity yellow and blue lights (Fig. 1). Light treatments significantly affected the reproductive biology of *C. montrouzieri* (Table 2). The total pre-oviposition period (TPOP) varied from 69.9 days under white-350 lux to 112.5 days under blue-690 lux. TPOP values under white-230, white-350, and white-460 lux were not significantly different from each other, while the longest pre-oviposition periods were recorded under yellow-230 lux, yellow-350 lux, yellow-460 lux, yellow-690 lux, blue-230 lux, blue-350 lux, blue-460 lux, and blue-690 lux. The oviposition period ranged from 44.8 days (blue-230 lux) to 69.6 days (white-690 lux). Treatments white-230 lux, white-350 lux, white-460 lux, white-690 lux, yellow-230 lux, yellow-350 lux, yellow-460 lux, yellow-690 lux, and blue-690 lux did not differ significantly, indicating similar oviposition duration, while blue-230 lux, blue-350 lux, and blue-460 lux also showed no significant differences among themselves. Post-oviposition periods ranged from 18.9 days (white-690 lux) to 48.6 days (white-230 lux), with several groups, including white-230 lux and White-350 lux, as well as blue-230 lux, blue-350 lux, blue-460 lux, and blue-690 lux, showing nonsignificant differences. Fecundity was highest under white-230 lux (221.4 eggs/female), followed by white-350 lux (185.3 eggs/female), which was significantly lower than white-230 lux but significantly higher than all remaining treatments and lowest under yellow-690 lux (81.9 eggs/female) and yellow-460 lux (88.3 eggs/female). White-460 lux, white-690 lux, yellow-230 lux, yellow-350 lux, blue-230 lux, blue-350 lux, blue-460 lux, and blue-690 lux showed similar fecundity, indicating nonsignificant differences among these treatments. Daily fecundity followed a

similar trend, with the highest values observed under white-230 lux and the lowest under white-690 lux and yellow-690 lux. Egg mortality ranged from 0.1 (white-230 lux) to 0.4 (yellow-460 lux and yellow-690 lux). Overall, lower-intensity White light (230–350 lux) favored shorter pre-oviposition periods, higher fecundity, and lower egg mortality. In contrast, higher light intensities (460–690 lux), as well as yellow or blue light, generally reduced reproductive performance.

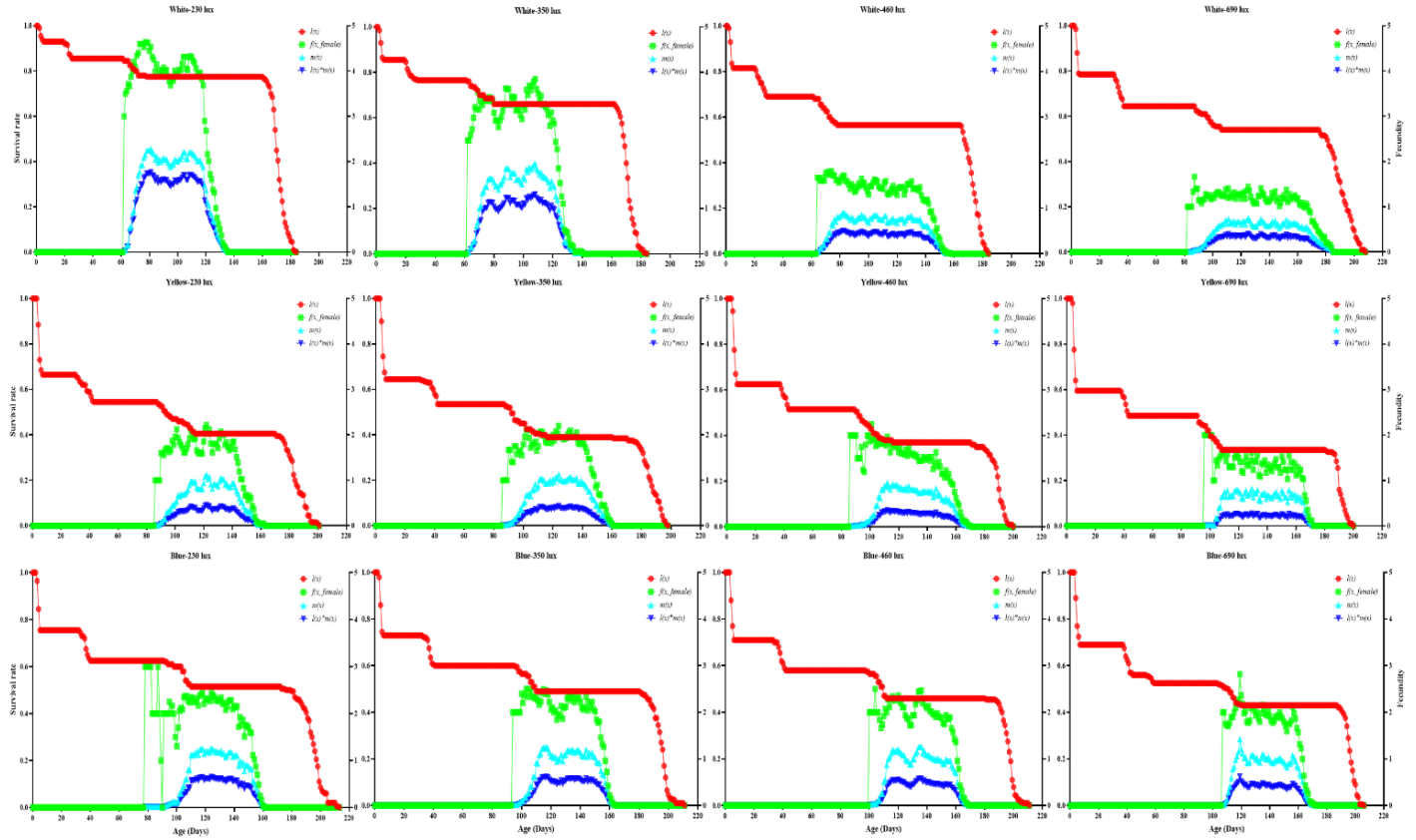


Figure 1: Age-specific survival rate (l_x), age-stage fecundity of female (f_x) (eggs/ female), age-specific fertility (m_x), and age-specific maternity ($l_x m_x$) of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments.

3.3. Population Growth Parameters Under Different Light Treatments

The population growth of *C. montrouzieri* fed on *D. opuntiae* was significantly influenced by light color and intensity (Table 3). The intrinsic rate of increase (r) was highest under white-230 lux, white-350 lux, and white-460 lux (0.049, 0.045, and 0.034 d^{-1} , respectively) and decreased progressively with higher light intensity and under yellow and blue light, reaching the lowest values under yellow-460 lux and yellow-690 lux (0.022 and 0.020 d^{-1} , respectively). The finite rate of increase (λ) mirrored the trend of r , with the highest values under white-230 lux, white-350 lux, and white-460 lux (1.050, 1.046, and 1.035 d^{-1} , respectively) and the lowest under yellow-460 lux and yellow-690 lux (1.022 and 1.020 d^{-1} , respectively). The net reproductive rate (R_0) and gross reproduction rate (GRR) were also affected by light treatments. The maximum R_0 was recorded under white-230 lux and white-350 lux (87.4 and 63.0 offspring per female, respectively), whereas the minimum was recorded under yellow-230 lux and yellow-690 lux (19.2 and 13.9 offspring per female, respectively). Similarly, GRR was highest under white-230 lux and white-350 lux (91.0 and 94.6 eggs per female, respectively) and lowest under yellow-690 lux (41.4 eggs per female). Mean generation time (T) varied depending on light conditions. The shortest generation times were observed under white-230 lux, white-350 lux, and white-460 lux (112.5, 92.7, and 100.7 days, respectively), while the longest was recorded under blue-690 lux (135.4 days). Overall, white light at low intensities (230–350 lux) promoted higher population growth, whereas yellow and blue light, especially at higher intensities (460–690 lux), suppressed growth and extended generation time.

3.4. Feeding Potential of *C. montrouzieri* Under Different Light Treatments

The feeding potential of *C. montrouzieri* on *D. opuntiae* varied significantly with light color and intensity (Table 4). Overall, the predator consumed the highest number of cochineal eggs, followed by first- and second-instar nymphs, with adult females being the least consumed stage. Under white-230 lux, a single individual of *C. montrouzieri* consumed the highest number of eggs (8926.1 eggs), 1st instar nymphs (8739.3 nymphs), 2nd instar nymphs (7404.6 nymphs), and adult females (349.1 females). As light intensity increased, the consumption of all cochineal stages progressively decreased, with the lowest numbers observed under blue-690 lux: eggs (5968.1 eggs), 1st instar nymphs (5922.0 nymphs), 2nd instar nymphs (5200.5 nymphs), and adult females (200.2 females). Yellow light generally supported slightly higher consumption than blue light but lower than white light at comparable intensities. For example, under yellow-230 lux, eggs (8811.3 eggs) and first-instar nymphs (8663.3 nymphs) were consumed at levels similar to white-230 lux. Across all treatments, adult females were consistently consumed in much lower numbers than eggs and nymphs.

Table 4: Estimated total number ($\pm$ SE) of different stages of *Dactylopius opuntiae* consumed by a single individual of *Cryptolaemus montrouzieri* over its whole life cycle under different light treatments.

Treatments (Color Intensity (Lux))	Cochineal Eggs	1st Instar Nymph	2nd Instar Nymph	Adult Females
White-230 lux	8926.1 $\pm$ 16.9 A	8739.3 $\pm$ 14.7 A	7404.6 $\pm$ 10.3 A	349.1 $\pm$ 1.3 A
White-350 lux	8490.6 $\pm$ 15.5 C	8362.4 $\pm$ 24.9 B	7105.7 $\pm$ 6.5 C	322.1 $\pm$ 1.4 B
White-460 lux	8015.0 $\pm$ 11.7 E	7923.5 $\pm$ 17.4 D	6796.4 $\pm$ 8.8 E	289.1 $\pm$ 1.1 D
White-690 lux	7433.7 $\pm$ 10.2 G	7403.2 $\pm$ 17.3 F	6394.3 $\pm$ 7.5 G	253.5 $\pm$ 1.3 F
Yellow-230 lux	8811.3 $\pm$ 14.1 B	8663.3 $\pm$ 19.1 A	7349.3 $\pm$ 10.3 B	345.1 $\pm$ 1.9 A
Yellow-350 lux	8338.3 $\pm$ 15.8 D	8154.6 $\pm$ 16.9 C	7044.3 $\pm$ 6.9 D	314.9 $\pm$ 1.1 C
Yellow-460 lux	7803.6 $\pm$ 17.7 F	7710.9 $\pm$ 18.3 E	6700.1 $\pm$ 9.4 F	283.6 $\pm$ 1.3 D
Yellow-690 lux	7292.8 $\pm$ 12.5 I	7209.9 $\pm$ 14.6 G	6306.4 $\pm$ 7.5 H	250.2 $\pm$ 1.1 F
Blue-230 lux	7426.3 $\pm$ 16.1 H	7321.2 $\pm$ 21.2 F	6300.7 $\pm$ 5.6 H	271.6 $\pm$ 1.0 E
Blue-350 lux	6996.7 $\pm$ 12.2 J	6908.3 $\pm$ 17.0 H	6009.2 $\pm$ 6.7 I	250.8 $\pm$ 1.2 F
Blue-460 lux	6496.8 $\pm$ 9.3 K	6377.0 $\pm$ 18.6 I	5604.1 $\pm$ 6.5 J	226.3 $\pm$ 1.1 G
Blue-690 lux	5968.1 $\pm$ 10.5 L	5922.0 $\pm$ 14.3 J	5200.5 $\pm$ 7.3 K	200.2 $\pm$ 1.0 H

Means within a column followed by the same small letter are not significantly different (Tukey's test, $p < 0.05$).

3.5. Morphometric Measurements and Body Weight Under Different Light Treatments

The morphometric traits of *C. montrouzieri* were significantly influenced by light color and intensity (Table 5). Overall, body length and width increased with the developmental stage of the predator, with the largest individuals observed in adults and fourth-instar larvae, and the smallest in first-instar larvae. White and yellow light, particularly at lower intensities (230–350 lux), generally produced larger body sizes across all developmental stages. Under white-230 lux, adult *C. montrouzieri* measured 5.7 mm in length and 3.4 mm in width, while under blue-690 lux, adults were smaller (5.3 mm length and 3.2 mm width). Higher light intensities and blue light were associated with slightly reduced body dimensions in all stages, particularly in early instars. Similarly, the body weight of *C. montrouzieri* varied according to light treatments (Table 6). Adult and fourth-instar larvae consistently had the highest body weights, while first-instar larvae were the lightest. White-230 lux produced the heaviest adults (5.7 mg) and fourth-instar larvae (3.7 mg), whereas blue-690 lux resulted in the lowest body weights across most stages, including adults (5.3 mg) and fourth-instar larvae (3.4 mg). Across all treatments, there was a gradual increase in body weight with predator development, and lower light intensities (230-350 lux) generally favored heavier individuals compared to higher intensities (460-690 lux).

Table 5: Estimated morphometric measurements (mean $\pm$ SE) of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments.

Treatments (Color-Intensity (Lux))	1st Instar Larva		2nd Instar Larva		3rd Instar Larva		4th Instar Larva		Adult	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)
White-230	2.2 $\pm$ 0.01 A	1.7 $\pm$ 0.01 A	4.3 $\pm$ 0.01 A	2.2 $\pm$ 0.01 A	6.0 $\pm$ 0.02 A	2.8 $\pm$ 0.01 A	8.6 $\pm$ 0.01 A	3.9 $\pm$ 0.01 A	5.7 $\pm$ 0.01 A	3.4 $\pm$ 0.01 A
White-350	2.1 $\pm$.01 AB	1.7 $\pm$ 0.01 AB	4.2 $\pm$ 0.01 BC	2.2 $\pm$ 0.01 AB	6.0 $\pm$ 0.02 AB	2.8 $\pm$ 0.01 ABC	8.6 $\pm$ 0.01 BC	3.8 $\pm$ 0.01 AB	5.6 $\pm$ 0.01 BC	3.4 $\pm$ 0.01 AB
White-460	2.0 $\pm$ 0.01 CD	1.7 $\pm$ 0.01 AB	4.2 $\pm$ 0.01 D	2.2 $\pm$ 0.01 BC	5.9 $\pm$ 0.02 BC	2.7 $\pm$ 0.01 BC	8.5 $\pm$ 0.01 DE	3.8 $\pm$ 0.01 BC	5.5 $\pm$ 0.01 DE	3.3 $\pm$ 0.01 BCD
White-690	2.0 $\pm$ 0.01 DE	1.6 $\pm$ 0.01 CD	4.2 $\pm$ 0.01 EF	2.2 $\pm$ 0.01 CD	5.8 $\pm$ 0.01 CDEF	2.7 $\pm$ 0.01 EF	8.5 $\pm$ 0.01 EF	3.8 $\pm$ 0.01 DE	5.5 $\pm$ 0.01 EF	3.3 $\pm$ 0.01 E
Yellow-230	2.1 $\pm$ 0.01 AB	1.7 $\pm$ 0.01 A	4.3 $\pm$ 0.01 AB	2.2 $\pm$ 0.01 A	6.0 $\pm$ 0.02 A	2.8 $\pm$ 0.01 AB	8.6 $\pm$ 0.01 AB	3.9 $\pm$ 0.01 A	5.6 $\pm$ 0.01 AB	3.4 $\pm$ 0.01 ABC
Yellow-350	2.1 $\pm$ 0.01 BC	1.7 $\pm$ 0.01 AB	4.2 $\pm$ 0.01 CD	2.2 $\pm$ 0.01 AB	5.9 $\pm$ 0.01 BCD	2.7 $\pm$ 0.01 CD	8.5 $\pm$ 0.01 CD	3.8 $\pm$ 0.01 AB	5.6 $\pm$ 0.01 CD	3.3 $\pm$ 0.01 ABC
Yellow-460	2.0 $\pm$ 0.01 CDE	1.7 $\pm$ 0.01 BC	4.2 $\pm$ 0.01 E	2.2 $\pm$ 0.01 C	5.8 $\pm$ 0.02 CDEF	2.7 $\pm$ 0.01 DE	8.5 $\pm$ 0.01 E	3.8 $\pm$ 0.01 BCD	5.5 $\pm$ 0.01 EF	3.3 $\pm$ 0.01 CD
Yellow-690	2.0 $\pm$ 0.01 DE	1.6 $\pm$ 0.01 CD	4.1 $\pm$ 0.01 F	2.1 $\pm$ 0.01 DE	5.8 $\pm$ 0.02 EF	2.7 $\pm$ 0.01 EFG	8.4 $\pm$ 0.01 FG	3.8 $\pm$ 0.01 EF	5.5 $\pm$ 0.01 FG	3.3 $\pm$ 0.01 DE
Blue-230	2.0 $\pm$ 0.01 EF	1.6 $\pm$ 0.01 DE	4.2 $\pm$ 0.01 E	2.1 $\pm$ 0.01 E	5.9 $\pm$ 0.02 CDE	2.7 $\pm$ 0.01 FGH	8.4 $\pm$ 0.01 GH	3.8 $\pm$ 0.01 CDE	5.5 $\pm$ 0.01 FG	3.3 $\pm$ 0.01 EF
Blue-350	1.9 $\pm$ 0.01 FG	1.6 $\pm$ 0.01 EF	4.1 $\pm$ 0.01 G	2.1 $\pm$ 0.01 E	5.8 $\pm$ 0.02 DEF	2.6 $\pm$ 0.01 GH	8.3 $\pm$ 0.01 H	3.8 $\pm$ 0.01 EF	5.5 $\pm$ 0.01 G	3.2 $\pm$ 0.01 FG
Blue-460	1.9 $\pm$ 0.01 G	1.6 $\pm$ 0.01 FG	4.0 $\pm$ 0.01 H	2.1 $\pm$ 0.01 F	5.8 $\pm$ 0.02 FG	2.6 $\pm$ 0.01 H	8.3 $\pm$ 0.01 I	3.8 $\pm$ 0.01 F	5.4 $\pm$ 0.01 H	3.2 $\pm$ 0.01 GH
Blue-690	1.8 $\pm$ 0.01 H	1.6 $\pm$ 0.01 G	4.0 $\pm$ 0.01 I	2.0 $\pm$ 0.01 G	5.7 $\pm$ 0.02 G	2.6 $\pm$ 0.01 I	8.2 $\pm$ 0.01 J	3.7 $\pm$ 0.01 G	5.3 $\pm$ 0.01 I	3.2 $\pm$ 0.01 H

Means within a columns followed by the same small letter are not significantly different (Tukey's test, $p < 0.05$).

Table 6: Mean body weight of *Cryptolaemus montrouzieri* fed on *Dactylopius opuntiae* under different light treatments.

Treatments (Color-Intensity (Lux))	1st Instar Larva	2nd Instar Larva	3rd Instar Larva	4th Instar Larva	Adult
White-230	0.6 $\pm$ 0.004	1.3 $\pm$ 0.014 A	2.4 $\pm$ 0.012 A	3.7 $\pm$ 0.022 A	5.7 $\pm$ 0.020 A
White-350	0.5 $\pm$ 0.004 AB	1.3 $\pm$ 0.012 ABC	2.4 $\pm$ 0.011 A	3.6 $\pm$ 0.019 AB	5.6 $\pm$ 0.026 AB
White-460	0.5 $\pm$ 0.006 BC	1.3 $\pm$ 0.012 ABCDE	2.3 $\pm$ 0.012 BC	3.6 $\pm$ 0.016 BC	5.5 $\pm$ 0.022 BC
White-690	0.5 $\pm$ 0.005 DE	1.3 $\pm$ 0.013 BCDEF	2.3 $\pm$ 0.010 CDE	3.5 $\pm$ 0.020 CDE	5.6 $\pm$ 0.022 BCD
Yellow-230	0.5 $\pm$ 0.004 AB	1.3 $\pm$ 0.010 AB	2.4 $\pm$ 0.015 AB	3.6 $\pm$ 0.023 AB	5.6 $\pm$ 0.019 AB
Yellow-350	0.5 $\pm$ 0.003 C	1.3 $\pm$ 0.012 ABCD	2.3 $\pm$ 0.011 BC	3.6 $\pm$ 0.015 ABC	5.5 $\pm$ 0.017 BC
Yellow-460	0.5 $\pm$ 0.004 CD	1.2 $\pm$ 0.010 DEF	2.3 $\pm$ 0.016 CDE	3.5 $\pm$ 0.015 CDE	5.4 $\pm$ 0.016 CD
Yellow-690	0.5 $\pm$ 0.005 E	1.2 $\pm$ 0.010 F	2.3 $\pm$ 0.013 DEF	3.5 $\pm$ 0.022 DEF	5.4 $\pm$ 0.017 DE
Blue-230	0.5 $\pm$ 0.004 CD	1.3 $\pm$ 0.012 ABCDE	2.3 $\pm$ 0.017 BC	3.5 $\pm$ 0.015 BCD	5.5 $\pm$ 0.023 BC
Blue-350	0.5 $\pm$ 0.005 E	1.2 $\pm$ 0.012 CDEF	2.3 $\pm$ 0.016 CD	3.5 $\pm$ 0.015 CDE	5.4 $\pm$ 0.020 CD
Blue-460	0.5 $\pm$ 0.004 E	1.2 $\pm$ 0.012 EF	2.2 $\pm$ 0.012 EF	3.4 $\pm$ 0.016 EF	5.4 $\pm$ 0.023 CD
Blue-690	0.4 $\pm$ 0.005 F	1.2 $\pm$ 0.010 F	2.2 $\pm$ 0.012 F	3.4 $\pm$ 0.024 F	5.3 $\pm$ 0.021 E

Means within a column followed by the same small letter are not significantly different (Tukey's test, $p < 0.05$).

4. Discussion

Our results show that both the colour and intensity of light substantially affect the life history, reproduction, and predatory capacity of *C. montrouzieri* feeding on *D. opuntiae*, echoing earlier evidence that photoperiod, intensity, and wavelength act as key environmental cues governing development, survival, and reproduction in predatory insects such as ladybirds and anthocorids [10, 41]. Development proceeded fastest under low-intensity white light (230–350 lux) and was delayed under blue and yellow light, especially at the higher intensities tested (460–690 lux). This contrasts somewhat with reports for other predatory ladybirds, in which nearly every individual completed its life cycle irrespective of the light regime, and where long photoperiods and high intensity actually favoured development, reproduction, locomotion, and predation [8]; it has similarly been suggested that light environments resembling the natural habitat, chiefly white and yellow, benefit ladybird life-history traits and could improve mass-rearing outcomes [8, 10]. Body size and weight followed a comparable pattern, with low-intensity white and yellow light (230–350 lux) yielding larger, heavier beetles and blue or high-intensity light producing smaller, lighter ones, paralleling findings in *H. variegata* and *H. axyridis*, where 16-h photoperiods and intensities up to 600 lux enhanced growth while extreme conditions compromised certain traits [8, 23, 42], and broadly consistent with *Orius* spp., where intensities as high as 5,000 lux sped up early development but could also induce stress or lengthen the pre-oviposition period under unfavourable wavelengths [11]. One plausible explanation for the prolonged development observed under high-intensity blue light (690 lux) is physiological stress, mirroring reports from other insects exposed to comparable conditions [43, 44]; however, because stress markers, oxidative damage, and cause of mortality were not directly measured here, this explanation should be treated as a reasonable interpretation grounded in the wider mechanistic literature rather than a mechanism demonstrated in *C. montrouzieri* itself. Elsewhere, excessive blue-light exposure has been linked to physiological damage [45], shortened lifespan [41], and elevated mortality [43, 44]. Raising LED brightness from 1,000 to 5,000 lux in *Orius sauteri* (Poppius) (Heteroptera: Anthocoridae) sped up nymphal development, shortened both the pre-oviposition period and copulation, and boosted five-day fecundity and movement speed, but at the cost of reduced egg viability, leading the authors to recommend shading eggs or moving them away from the most intensely lit areas [11]; by comparison, *Orius majusculus* (Reuter) kept under fluorescent light at either 10–200 lux or 2,400 lux showed no clear pattern in reproduction or longevity, aside from slower nymphal development at 200 lux [46].

Pre-adult survival and reproductive output peaked under low-intensity white light (230–350 lux), where females matured earlier, laid more eggs, and produced eggs of higher viability, whereas high-intensity blue and yellow light depressed both survival and reproduction, plausibly through physiological stress or reduced prey intake, a pattern that fits earlier observations in other predatory insects [10, 47]. Part of this variation in reproductive traits may stem from an interaction between photoperiod and wavelength that feeds into diapause regulation or reproductive physiology more broadly [8]: in *Orius insidiosus* (Say), for example, shortened photoperiods or dim blue light suppress diapause, while intense blue or red light can trigger stress responses resembling diapause [48]. Diapause was not observed in the present experiments, but the extended pre-oviposition period recorded under high-intensity blue light could reflect a related physiological constraint. Elevated light intensity has also been reported to reduce fertility in *O. sauteri* via impaired egg viability [11], whereas in *H. variegata* the opposite occurred: fecundity doubled under high intensity (1.5–1.8 W m²), and egg hatch peaked at intermediate intensity (0.8–1.2 W m²) [8]. Because several studies link high ladybird fertility to large sperm loads or seminal vesicles transferred during mating [11, 23], and because sperm transfer, sperm load, and vesicle size were not measured here, we raise the following purely as an untested hypothesis: light intensity might alter the efficiency of sperm transfer during copulation, and females receiving less sperm could lay additional eggs to offset this loss. This proposed compensatory response is speculative and would need to be tested directly in future work [8].

Wavelength effects also appear to be species-specific: in *H. variegata*, longer wavelengths (red and yellow) impaired development relative to short-wavelength purple light, while green light, which approximates light filtered through a plant canopy, proved most favourable [8] — a pattern that does not match *O. sauteri*, where blue and yellow light produced different outcomes [11], suggesting that responses to wavelength diverge not only between species but potentially between insect orders such as Hemiptera and Coleoptera. White light, meanwhile, has separately been identified as most favourable for development and reproduction in the ladybirds *Propylea*

dissecta (Mulsant) and *Coccinella sexmaculata* Linnaeus (Coleoptera: Coccinellidae) [3], and longer wavelengths have more generally been reported to hinder development and feeding in fruit flies, moths, and coccinellids alike [3, 15].

For greenhouse operations and mass-rearing facilities alike, these results carry clear practical weight. Moderate-intensity white light (230–350 lux) offers the best combination of rapid development, strong survival, efficient reproduction, and effective predation of *D. opuntiae* by *C. montrouzieri*, whereas high-intensity blue or yellow light, or spectra that depart from natural daylight, tend to compromise predator growth and performance — a pattern echoed in other beneficial species such as *H. variegata* and *O. sauteri* [10]. Rearing facilities could therefore benefit from deliberately tuning colour spectrum, intensity, and photoperiod to boost both production and the eventual field performance of this biocontrol agent. Illumination systems designed for plant cultivation are already common in greenhouse vegetable production [49, 50], but the kind of systematic evaluation of light intensity and wavelength effects on *C. montrouzieri* undertaken here remains necessary to gauge how lighting choices translate into practical gains for predatory ladybirds. It would also be worth examining how light affects the host plants themselves, and thereby the pests that feed on them through plant tissue or volatile cues, since these indirect pathways could equally shape the behaviour, life history, and population dynamics of natural enemies. As LED lighting management becomes more widely adopted, fine-tuning environmental conditions is likely to become an increasingly important lever for improving the efficiency of commercial natural-enemy rearing.

From an applied standpoint, the practical adoption of tailored lighting in commercial *C. montrouzieri* mass-rearing units also depends on cost and scalability. White LED or fluorescent fixtures operating at the low intensities identified here as optimal (230–350 lux) draw substantially less electrical power than higher-intensity or coloured alternatives, so the same lighting change that improves developmental and reproductive performance is also likely to reduce energy costs per unit of production, an important consideration for commercial insectaries operating at scale. Retrofitting existing rearing rooms with low-intensity white lighting is a relatively low-cost intervention compared with, for example, changes to diet or temperature control, which strengthens the case for rapid uptake by producers. It should be noted, however, that the light environment experienced by *C. montrouzieri* after release into a greenhouse or open field—where spectral composition, intensity, and photoperiod are set by sunlight and, in greenhouses, by supplemental horticultural LED lighting installed for the crop rather than for the natural enemy—will generally differ substantially from the controlled 230–350 lux white-light conditions tested here. The findings reported in this study should therefore be interpreted as guidance for indoor mass-rearing conditions in the first instance, and extrapolation to post-release performance in greenhouse or field settings will require additional validation under those specific lighting regimes.

Several limitations of this study should be acknowledged. First, all experiments were conducted under controlled laboratory conditions (25 ± 1 °C, $66 \pm 5\%$ relative humidity, 16:8 h light:dark), and the life-history and predation responses reported here may not translate directly to the more variable temperature, humidity, and light conditions encountered in greenhouses or the field. Second, light treatments were tested under only one temperature/relative-humidity regime, so any interaction between light and these other abiotic factors could not be assessed and remains an open question for future work. Third, because each light colour $\times$ intensity combination was assigned to a single rearing room for the full duration of a life cycle, with rooms sequentially reassigned to the next treatment rather than randomised or replicated concurrently, room and time (cohort sequence) are confounded with treatment in this design; no formal blocking or random-effects structure was applied, and carry-over effects between successive treatments occupying the same room cannot be ruled out. Replication was achieved by repeating each treatment twice at different times rather than by concurrent replication across multiple rooms, which further limits the extent to which room-specific effects can be distinguished from true treatment effects. Fourth, the predation trials reported here were conducted under free-choice conditions in small Petri dishes, which cannot capture the spatial complexity, prey patchiness, and interference from non-target organisms typical of field foraging; predation rates and prey preferences observed in the laboratory should therefore be regarded as indicative of relative treatment effects rather than as direct estimates of field predation capacity.

5. Conclusion

In conclusion, our study demonstrates that the light environment strongly influences the biology and predatory efficiency of *C. montrouzieri*. Low-intensity white light (230–350 lux) optimizes growth, reproduction, and prey consumption, whereas high-intensity or colored lights, particularly blue and yellow, induce stress, delay development, and reduce reproductive performance. These findings can improve mass-rearing practices and enhance the effectiveness of *C. montrouzieri* in biological control of *D. opuntiae*. Future research should determine the optimal light characteristics for artificial production, quantify egg hatch, nymphal development, and predation efficiency, and investigate the physiological and environmental interactions affecting predator performance to support integrated pest management strategies.

Author Contributions

Mohamed El Aalaoui: Conceptualization; literature search and synthesis; writing – original draft; writing – review and editing.

Mohamed Sbaghi: Conceptualization; visualization; writing – review and editing.

Conflict of Interest

There is no competitive interest regarding this manuscript.

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Availability of Data

Original data for the manuscript can be obtained from the corresponding author upon reasonable request.

References

- [1] Tobe S, Pratt G. The influence of substrate concentrations on the rate of insect juvenile hormone biosynthesis by corpora allata of the desert locust in vitro. *Biochem J.* 1974; 144: 107-13. <https://doi.org/10.1042/bj1440107>
- [2] Dudd J, Shure D. The influence of light and nutrients on foliar phenolics and insect herbivory. *Ecology.* 1994; 75: 86-98. <https://doi.org/10.2307/1939385>
- [3] Omkar, Mishra G, Singh K. Effects of different wavelengths of light on the life attributes of two aphidophagous ladybirds (Coleoptera: Coccinellidae). *Eur J Entomol.* 2005; 102: 33-7. <https://doi.org/10.14411/eje.2005.005>
- [4] Huynh MP, Pereira AE, Geisert RW, Vella MG, Coudron TA, Shelby KS, *et al.* Characterization of thermal and time exposure to improve artificial diet for western corn rootworm larvae. *Insects.* 2021; 12: 783. <https://doi.org/10.3390/insects12090783>
- [5] Parra JRP, Coelho Jr A. Insect rearing techniques for biological control programs, a component of sustainable agriculture in Brazil. *Insects.* 2022; 13(1): 105. <https://doi.org/10.3390/insects13010105>
- [6] Charvalakis GA, Stavenga DG, Visser ME, Spoelstra K, Hut RA. Intensity and colour of artificial light at night affect insect attraction in a taxon-dependent manner. *Insect Conserv Divers.* 2025; 1-10. <https://doi.org/10.1111/icad.12855>
- [7] Henneberry T, Clayton T. Time of emergence, mating, sperm movement, and transfer of ejaculatory duct secretory fluid by *Heliothis virescens* (F.) (Lepidoptera: Noctuidae) under reversed light-dark cycle laboratory conditions. *Ann Entomol Soc Am.* 1984; 77: 301-5. <https://doi.org/10.1093/aesa/77.3.301>
- [8] Tan X, Zhao J, Zhang F, Wang S. Light dependency of life traits, reproduction, locomotion, and predation in the polyphagous ladybird *Hippodamia variegata*. *Entomol Exp Appl.* 2014; 152(3): 200-8. <https://doi.org/10.1111/eea.12217>
- [9] Pathak S. Effects of different photoperiods and wavelengths of light on the life-history traits of an aphidophagous ladybird, *Coelophora saucia* (Mulsant). *J Appl Entomol.* 2006; 130: 45-50. <https://doi.org/10.1111/j.1439-0418.2005.01016.x>
- [10] Wang S, Tan X-L, Guo X-J, Zhang F. Effect of temperature and photoperiod on the development, reproduction, and predation of the predatory ladybird *Cheilomenes sexmaculata* (Coleoptera: Coccinellidae). *J Econ Entomol.* 2013a; 106: 2621-9. <https://doi.org/10.1603/EC13095>

- [11] Wang S, Tan X, Michaud J, Zhang F. Light intensity and wavelength influence development, reproduction and locomotor activity in the predatory flower bug *Orius sauteri* (Poppus) (Hemiptera: Anthocoridae). *BioControl*. 2013b; 58: 667-74. <https://doi.org/10.1007/s10526-013-9522-2>
- [12] Franzmann BA. *Hippodamia variegata* (Goeze) (Coleoptera: Coccinellidae), a predacious ladybird new in Australia. *Aust J Entomol*. 2002; 41: 375-7. <https://doi.org/10.1046/j.1440-6055.2002.00318.x>
- [13] Kontodimas D, Stathas G. Phenology, fecundity and life table parameters of the predator *Hippodamia variegata* reared on *Dysaphis crataegi*. *BioControl*. 2005; 50: 223-33. <https://doi.org/10.1007/s10526-004-0455-7>
- [14] Lunau K, Wacht S. Innate flower recognition in the hoverfly *Eristalis tenax* L. *Mitt Dt Ges Allg Angew Entomol*. 1997; 11: 481-4.
- [15] Sakai T, Isono K, Tomaru M, Fukatami A, Oguma Y. Light wavelength dependency of mating activity in the *Drosophila melanogaster* species subgroup. *Genes Genet Syst*. 2002; 77: 187-95. <https://doi.org/10.1266/ggs.77.187>
- [16] Mondor EB, Warren JL. Unconditioned and conditioned responses to colour in the predatory coccinellid, *Harmonia axyridis* (Coleoptera: Coccinellidae). *Eur J Entomol*. 2000; 97: 463-7. <https://doi.org/10.14411/eje.2000.071>
- [17] Omkar, Mishra G. Ovipositional orientation of an aphidophagous ladybird beetle, *Propylea dissecta* (Mulsant). *Insect Sci Appl*. 2003; 23: 211-9. <https://doi.org/10.1017/S1742758400023614>
- [18] Omkar, Mishra G, Srivastava S, Gupta AK. Ovipositional rhythmicity in ladybirds (Coleoptera: Coccinellidae): a laboratory study. *Biol Rhythm Res*. 2004; 35(4-5): 277-87. <https://doi.org/10.1080/09291010400003487>
- [19] Pervez A, Omkar S. Prey-dependent life attributes of an aphidophagous ladybird beetle, *Propylea dissecta* (Mulsant). *Biocontrol Sci Technol*. 2004a; 14: 385-96. <https://doi.org/10.1080/09583150410001683547>
- [20] Pervez A, Omkar, Richmond AS. The influence of age on reproductive performance of a predatory ladybird beetle, *Propylea dissecta*. *J Insect Sci*. 2004; 4(22): 1-8. <https://doi.org/10.1673/031.004.2201>
- [21] Danks HV. *Insect Dormancy: An Ecological Perspective*. Biological Survey of Canada (Terrestrial Arthropods), National Museum of Natural Sciences, Ottawa. 1987; 439 pp.
- [22] Muller HJ. *Dormanz bei Arthropoden*. Gustav Fischer Verlag, Jena, Stuttgart, New York. 1992; 289 pp.
- [23] Wang S, Michaud J, Zhang R, Zhang F, Liu S. Seasonal cycles of assortative mating and reproductive behaviour in polymorphic populations of *Harmonia axyridis* in China. *Ecol Entomol*. 2009; 34: 483-94. <https://doi.org/10.1111/j.1365-2311.2008.01075.x>
- [24] Clausen CP. *Introduced parasites and predators of arthropod pests and weeds: a world review*. United States Department of Agriculture, Washington, USA. 1978.
- [25] Baskaran RKM, Lakshmi LG, Uthamasamy S. Comparative biology and predatory potential of Australian ladybird beetle (*Cryptolaemus montrouzieri*) on *Planococcus citri* and *Dactylopius tomentosus*. *Indian J Agric Sci*. 1999; 69: 605-6.
- [26] Solangi GS, Lohar MK, Abro GH, Buriro AS. Biology and release of exotic predator *Cryptolaemus montrouzieri* Mulsant on mealybug *Phenacoccus solenopsis* Tinsley at Tandojam. *Sarhad J Agric*. 2012; 28: 429-35.
- [27] Mendel Z, Protasov A, Golan O, Bensimon D, Kolodny O, Suma P. Navigating challenges in the management of *Dactylopius opuntiae* (Cockerell): Transitioning from 'introduction biological control' to a preemptive strategy of artificial seeding of a natural enemy. *Biol Control*. 2024; 196: 105582. <https://doi.org/10.1016/j.biocontrol.2024.105582>
- [28] Torres JB, Giorgi JA. Management of the false carmine cochineal *Dactylopius opuntiae* (Cockerell): perspective from Pernambuco state, Brazil. *Phytoparasitica*. 2018; 46(3): 331-40. <https://doi.org/10.1007/s12600-018-0664-8>
- [29] Protasov A, Mendel Z, Spodek M, Carvalho CJ. Management of the *Opuntia* cochineal scale insect, *Dactylopius opuntiae* (Cockerell) in Israel. *Alon Hanotea*. 2017; 71: 48-51.
- [30] Harbi A, Abbes K, Rahmouni R, Chermiti B. Life table and population growth parameters of *Cryptolaemus montrouzieri* on *Dactylopius opuntiae* and *Phenacoccus solenopsis*: Insights for biological control. *Phytoparasitica*. 2025; 53(1): 1-14. <https://doi.org/10.1007/s12600-024-01222-x>
- [31] El Aalaoui M, Bouharroud R, Sbaghi M, El Bouhssini M, Hilali L, Dari K. First study of the biology of *Cryptolaemus montrouzieri* and its potential to feed on the mealybug *Dactylopius opuntiae* (Hemiptera: Dactylopiidae) under laboratory conditions in Morocco. *Arch Phytopathol Plant Prot*. 2019; 52(13-14): 1112-24. <https://doi.org/10.1080/03235408.2019.1691904>
- [32] Omkar, Mishra G. Preference-performance of a generalist predatory ladybird: a laboratory study. *Biol Control*. 2005; 34(2): 187-95. <https://doi.org/10.1016/j.biocontrol.2005.05.007>
- [33] Khan HAA, Sayyed AH, Akram W, Razald S, Ali M. Predatory potential of *Chrysoperla carnea* and *Cryptolaemus montrouzieri* larvae on different stages of the mealybug, *Phenacoccus solenopsis*: A threat to cotton in South Asia. *J Insect Sci*. 2012; 12(1): 147. <https://doi.org/10.1673/031.012.14701>
- [34] Aldama-Aguilera C, Llanderal-Cázares C. Grana cochinilla: comparación de métodos de producción en penca cortada. *Agro Ciencia*. 2003; 37(1): 11-9.
- [35] Seyfollahi F, Esfandiari M, Mossadegh MS, Rasekh A. Life table parameters of the coccinellid *Hyperaspis polita*, a native predator in Iran, feeding on the invasive mealybug *Phenacoccus solenopsis*. *J Asia-Pac Entomol*. 2016; 19(3): 835-840.
- [36] Chi HSIN, Liu HSI. Two new methods for the study of insect population ecology. *Bull Inst Zool Acad Sin*. 1985; 24(2): 225-40. <https://doi.org/10.1016/j.aspen.2016.07.008>

- [37] Chi H. Life-table analysis incorporating both sexes and variable development rates among individuals. *Environ Entomol.* 1988; 17(1): 26-34. <https://doi.org/10.1093/ee/17.1.26>
- [38] Chi H. TWOSEX-MSChart: a computer program for the age-stage, two-sex life table analysis. National Chung Hsing University, Taichung, Taiwan. 2021. Available at: <http://140.120.197.173/Ecology/Download/Twosex-MSChart.zip> (accessed 5 April 2021).
- [39] Goodman D. Optimal life histories, optimal notation, and the value of reproductive value. *Am Nat.* 1982; 119(6): 803-23. <https://doi.org/10.1086/283956>
- [40] Efron B, Tibshirani RJ. An introduction to the bootstrap. Chapman and Hall, New York. 1993; 456 pp. <https://doi.org/10.1007/978-1-4899-4541-9>
- [41] Nash TR, Chow ES, Law AD, Fu SD, Fuszara E, Bilska A, *et al.* Daily blue-light exposure shortens lifespan and causes brain neurodegeneration in *Drosophila*. *NPJ Aging Mech Dis.* 2019; 5: 8. <https://doi.org/10.1038/s41514-019-0038-6>
- [42] Aksit T, Cakmak I, Ozer G. Effect of temperature and photoperiod on development and fecundity of an acarophagous ladybird beetle, *Stethorus gilvifrons*. *Phytoparasitica.* 2007; 35: 357-66. <https://doi.org/10.1007/BF02980698>
- [43] Hori M, Shibuya K, Sato M, Saito Y. Lethal effects of short-wavelength visible light on insects. *Sci Rep.* 2014; 4: 7383. <https://doi.org/10.1038/srep07383>
- [44] Shibuya K, Onodera S, Hori M. Toxic wavelength of blue light changes as insects grow. *PLoS One.* 2018; 13: e0199266. <https://doi.org/10.1371/journal.pone.0199266>
- [45] Stark WS, Walker KD, Eidell JM. Ultraviolet and blue light induced damage to the *Drosophila* retina: microspectrophotometry and electrophysiology. *Curr Eye Res.* 1985; 4: 1059-75. <https://doi.org/10.3109/02713688509003351>
- [46] Bahşi ŞÜ, Tunç İ. The response of a southern strain of *Orius majusculus* (Reuter) (Hemiptera: Anthoridae) to photoperiod and light intensity: biological effects and diapause induction. *Biol Control.* 2012; 63: 157-63. <https://doi.org/10.1016/j.biocontrol.2012.06.007>
- [47] Dixon AFG. *Insect Predator-Prey Dynamics, Ladybird Beetles and Biological Control.* Cambridge University Press, New York. 2000; 257 pp.
- [48] Waite M. New strategies to improve the efficiency of the biological control agent, *Orius insidiosus* (Say), in greenhouse ornamental crops. Department of Environmental Biology, University of Guelph; 2012. <http://hdl.handle.net/10214/5080>
- [49] Külheim C, Agren J, Jansson S. Rapid regulation of light harvesting and plant fitness in the field. *Science.* 2002; 297: 91-3. <https://doi.org/10.1126/science.1072359>
- [50] Massa G, Kim H, Wheeler R, Mitchell C. Plant productivity in response to LED lighting. *HortScience.* 2008; 43: 1951-6. <https://doi.org/10.21273/HORTSCI.43.7.1951>