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ORIGINAL RESEARCH PAPER

Lethal effect of blue light on *Liposcelis bostrychophila* (Psocoptera: Liposcelididae)

Masatoshi Hori[1] · **Norihiro Oyama**[1]

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Abstract

We previously reported that blue light is lethal to various insect species. However, it was also revealed that effective blue light wavelength is species and growth-stage specific. We, therefore, investigated the lethal effects of blue light on booklice, *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae), which frequently occur in food processing and storage facilities, where insecticides cannot often be used because of the risk of their contamination on the food products. *Liposcelis bostrychophila* eggs were killed by irradiation with 408–462-nm blue light and 378-nm UVA at 5×10^{18} photons·m^{-2}·s^{-1}, with 100% mortality. In particular, 420-nm blue light had a strong lethal effect, showing 96.5% mortality at 1.5×10^{18} photons·m^{-2}·s^{-1}. The adults were killed by irradiation with 378–494-nm light at 5×10^{18} photons·m^{-2}·s^{-1}. Irradiation with 378–440-nm and 462-nm light showed 96%–100% mortality at this photon flux density. In particular, 378 and 408-nm light notably exhibited strong lethal effects, showing 100% and 87% mortality, respectively, at 3×10^{18} photons·m^{-2}·s^{-1}. These results show that blue light irradiation is useful for controlling booklice occurrence in food facilities. Additionally, this study revealed for the first time that blue-light irradiation is lethal to hemimetabolous insects.

Keywords Booklice · Short-wavelength visible light · Light-emitting diodes · Irradiation · Psocoptera

Introduction

Booklice, *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae), frequently occur in food processing and storage facilities, causing significant damage to stored commodities (Ahmedani et al. 2010). However, insecticides cannot often be used in these facilities because of contamination risk to the food products. In addition, stored product insect pests including the booklice, usually inhabit inside equipment such as food processing machines and switchboards, as well as in narrow spaces under the machines (Bell and Edwards 1999). It is, therefore, difficult to constantly recognize and effectively control their occurrence. Presently, insect pests in these facilities are controlled mainly by sanitation to remove their infestation source. However, sanitation is time consuming and labor intensive. Thus, there is a need to develop safer and cleaner alternatives such as physical pest control methods.

In recent years, the use of light for pest control has been studied along with the development and popularization of light-emitting diodes (LEDs). Light has been used for controlling insect pests for many years, given the attraction of insects to light sources and suppression of their nocturnal activities by yellow light (Shimoda and Honda 2013). Most practical light techniques utilize insect behavioral reactions to light and do not directly kill them (Hori 2016). The use of ultraviolet B (UVB, 280–315 nm) as a control technique in spider mites to directly kill them is currently in the preliminary stage (Tanaka et al. 2016). The lethal effect of ultraviolet C (UVC, 100–280 nm) on insects has been reported (Beard 1972; Bruce 1975; Calderon et al. 1985; Faruki et al. 2007; Ghanem and Shamma 2007; Nakajima and Yoshida 1971; Wharton 1971); however, UVC is yet to be practically used on them.

UVB and UVC are highly toxic to organisms, because they are absorbed by the DNA, thereby directly damaging it (Beggs 2002; Pfeifer 1997). Therefore, it is difficult to use UVB and UVC to kill insect pests in food processing and storage facilities because of the risks of safety hazards

✉ Masatoshi Hori
masatoshi.hori.a3@tohoku.ac.jp

[1] Graduate School of Agricultural Science, Tohoku University, Aramaki Aza Aoba 468-1, Aoba-Ku, Sendai, Miyagi 980-8572, Japan

posed to humans. The toxicity of UVA (315–400 nm) is much lower than that of UVB and UVC, because UVA does not directly damage the DNA (Rastogi et al. 2010; Sinha and Häder 2002). Furthermore, no reports, with the exception of a recent report on *Dialeurodes citri* (Ashmead) (Hemiptera: Aleyrodidae) (Tariq et al. 2015), have described the lethal effects of UVA on insects, except for a slight decrease in adult longevity of *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) following UVA irradiation (Zhang et al. 2011). It is well known that light with shorter wavelengths carry higher energies and therefore are more harmful to organisms (Clark 1922; McMillan et al. 2008; Reed 2010). Therefore, it had been considered that visible light (400–780 nm) does not have a lethal effect on complex animals, including insects (Hori et al. 2014). We discovered that short-wavelength visible light (blue light, 400–500 nm) can kill some insect species (Hori et al. 2014). To date, we have confirmed the lethal effect of blue light on more than ten insect species, including the fruit fly, *Drosophila melanogaster* Meigen (Diptera: Drosophilidae), the confused flour beetle, *Tribolium confusum* Duval (Coleoptera: Tenebrionidae) (Hori et al. 2014), the strawberry leaf beetle, *Galerucella grisescens* (Joannis) (Coleoptera: Chrysomelidae) (Hori and Suzuki 2017), the urban mosquito *Culex pipiens pipiens* form *molestus* Forskål (Diptera: Culicidae) (Taniyama et al. 2021), and the Asian tiger mosquito, *Aedes albopictus* (Skuse) (Diptera: Culicidae) (Taniyama and Hori 2022). These studies revealed that the highly toxic wavelengths and effective photon flux density of blue light vary depending on the insect species (Hori et al. 2014). Therefore, it is necessary to identify a highly effective wavelength and photon flux density of blue light for each target insect species to utilize the lethal effects of blue light for pest control in food facilities. Therefore, in this study, we investigated the effective wavelength and photon flux density of blue light to kill *L. bostrychophila* to develop practical blue light techniques for controlling the species.

Materials and methods

Insects

Liposcelis bostrychophila was supplied by Earth Environmental Service Co., Ltd. (Tokyo, Japan) in 2017 and was maintained in our laboratory. The booklice were reared in a plastic container (137 × 137 × 61 mm) on 50 g of a powdered rodent diet (CE-2, CLEA Japan, Inc., Tokyo, Japan). An absorbent cotton pad (0.2 g) soaked in water (2 mL) was placed in an aluminum foil cup (34 × 32 mm) and kept in the container to maintain a relative humidity of ~ 80%. Water (2 mL) was added to the cotton pad every 4 d. The cup with the cotton pad was replaced with a new one every 7 d. All stages of the booklice were maintained in an incubator (MIR-153, Sanyo Electric Co., Ltd., Osaka, Japan) at 27 ± 1 °C under dark conditions.

Light-emitting diode (LED) light radiation

LED lighting units (IS-mini®, ISL-150 × 150 Series; CCS Inc., Kyoto, Japan; light emission surface: 150 × 150 mm; arrangement: 360 LEDs equally arranged on a panel; LED type: φ 3 mm plastic mold) with power supply units (ISC-201-2; CCS Inc., Kyoto, Japan) were used for light radiation. The insects were irradiated with LED light in a multi-room incubator (LH-30CCFL-8CT; Nippon Medical & Chemical Instruments Co., Ltd., Osaka, Japan). The emission spectra and the light intensity (photons·m^{-2}·s^{-1}) were measured using a high-resolution spectrometer (HSU-100S; Asahi Spectra Co., Ltd., Tokyo, Japan; numerical aperture of the fiber: 0.2) in a dark room. The number of photons was adjusted using a power supply unit. During the measurements, the distance between the LED lighting unit and the spectrometer sensor was set to be approximately equal to the distance between the insects and LED lighting unit in the incubator. Because the tested insects were irradiated through the glass lid of a Petri dish, the same lid was placed between the light source and sensor during measurement. The number of photons was measured five times, and the mean values of each experiment are listed in Tables S1 and S2.

Lethal effect of blue-light irradiation on *L. bostrychophila* eggs

The eggs of *L. bostrychophila* were collected from stock cultures within 2 d of deposition. Ten eggs were placed on a sheet of filter paper (ADVANTEC®, No. 1, 55 mm in diameter, Toyo Roshi Kaisha, Ltd., Tokyo, Japan) impregnated with 30 µL of water in a lid of a glass Petri dish (50 mm in diameter) with a small amount (~ 10 mg) of powdered rodent diet (CE-2). The lid, with its base inverted, was placed over the Petri dish and sealed with Parafilm. The Petri dishes were placed in a multi-room incubator (25 ± 1 °C) and irradiated with LED light at peak wavelengths of 378 (UVA), 408, 420, 440, 456, 462, 494, 508 (blue green), 532 (green), or 594 nm (yellow), with set values of 1.5×10^{18} photons·m^{-2}·s^{-1}, 3×10^{18} photons·m^{-2}·s^{-1}, and 5×10^{18} photons·m^{-2}·s^{-1}. The irradiation period was set at 7 d, following which the Petri dishes were maintained under continuous darkness (DD) for 9 d (25 ± 1 °C), because their egg period was approximately 1–2 w (Wang et al. 2000). The number of hatchlings was then counted, and egg mortality was calculated. In the control treatment, the eggs were maintained under DD (i.e., no irradiation), as indicated previously (Hori and Suzuki 2017; Shibuya et al. 2018; Taniyama et al. 2021), at 25 ± 1 °C for 16 d, and mortality was calculated.

Ten replicates (Petri dishes) were performed for each light dose of every wavelength. The effects of 494–594 nm light at 1.5×10^{18} photons·m^{-2}·s^{-1} were not investigated, because their mortalities at 3×10^{18} photons·m^{-2}·s^{-1} were low. The effects of 532 and 594 nm light at 5×10^{18} photons·m^{-2}·s^{-1} were also not investigated, because the maximum photon flux density of the unit of these wavelengths was low.

Lethal effect of blue-light irradiation on *L. bostrychophila* adults

A sheet of filter paper (ADVANTEC®, No. 1, 55 mm in diameter, Toyo Roshi Kaisha, Ltd., Tokyo, Japan) impregnated with 40 µL of water was placed at the bottom of a glass Petri dish lid (50 mm in diameter), and a small amount (~ 10 mg) of powdered rodent diet (CE-2) was placed on the filter paper. Ten adults of *L. bostrychophila* from 1 to 7 d after eclosion were collected from the stock cultures and released on the filter paper. After releasing the insects, the lid, with its base inverted, was placed over the Petri dish and sealed with Parafilm. The Petri dishes were placed in a multi-room incubator (25 ± 1 °C) and irradiated with LED light at peak wavelengths of 378, 408, 420, 440, 456, 462, 494, 508, 532, or 594 nm, with a set value of 3×10^{18} photons·m^{-2}·s^{-1} or 5×10^{18} photons·m^{-2}·s^{-1}. The irradiation period was set at 6 d, because in the preliminary tests, 99% mortality was obtained by irradiation with 462-nm blue light at 5×10^{18} photons·m^{-2}·s^{-1} for 6 d. After irradiation, we counted the number of dead adults and calculated the mortality. In the control treatment, the eggs were maintained under DD (i.e., no irradiation) at 25 ± 1 °C for 6 d, and mortality was calculated. An adult booklouse was regarded as dead if the appendages did not move when touched with a calligraphy brush. Ten replicates (Petri dishes) were performed for each light dose of each wavelength. The effects of 532 and 594 nm light at 5×10^{18} photons·m^{-2}·s^{-1} were not investigated, because the maximum photon flux density of the unit of these wavelengths was low.

Statistical analysis

Irradiation treatments and controls were compared using the Steel test. Mortality rates in irradiation treatments were corrected using Abbott's formula (Abbott 1925) and compared among wavelengths using the Steel–Dwass test. Calculations were performed using R version 4.0.3 (R Development Core Team 2020).

Results

Lethal effect of blue-light irradiation on *L. bostrychophila* eggs

Continuous irradiation with 408–462-nm blue light, as well as 378-nm UVA, at 5×10^{18} photons·m^{-2}·s^{-1} remarkably increased booklice eggs mortality compared with the control (DD) mortality (Fig. 1). All the eggs were killed by irradiation in the above wavelength range at this photon flux density. In contrast, irradiation with 494 and 508 nm light at this photon flux density did not show a significant lethal effect ($p > 0.05$). Irradiation with wavelengths of 378–440 nm and 462 nm at 3×10^{18} photons·m^{-2}·s^{-1} also exhibited a strong lethal effect on the eggs, with more than 90% mortality. More precisely, irradiation with 378–440 nm light resulted in 100% mortality. Irradiation with 420-nm blue light, of

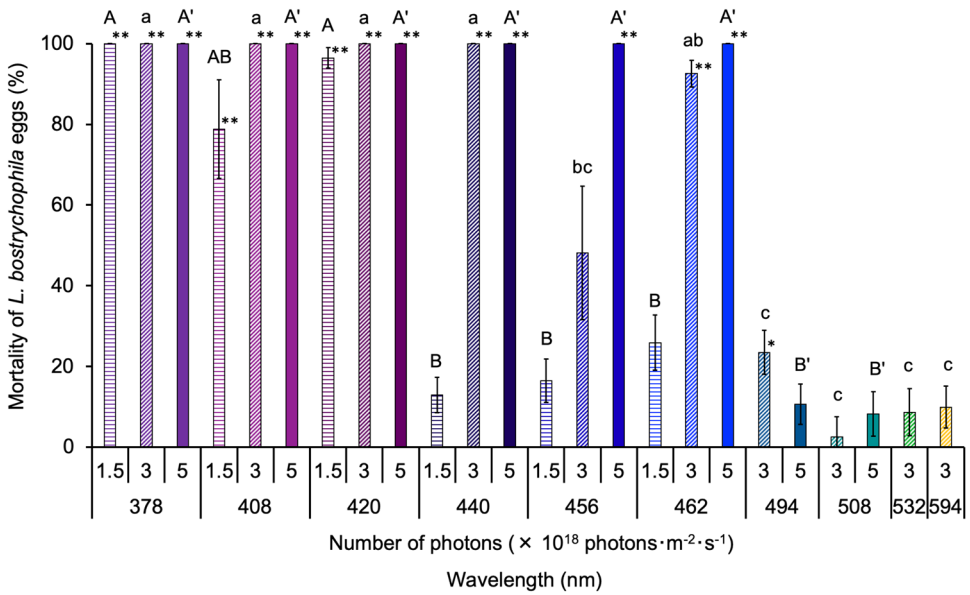

Fig. 1 Comparison of the lethal effects of light irradiation on *Liposcelis bostrychophila* eggs using various wavelengths of light. Data represent the means ± standard errors. Mortality rates in treatments (irradiation) were corrected using Abbott's formula (Abbott 1925). Asterisks above the bars indicate significant differences between the treatments and control (DD) (Steel test: * $p < 0.05$, ** $p < 0.01$). Mortality under DD was 16.3 ± 1.5 (%). Bars with same letters are not significantly different among the wavelengths (Steel–Dwass test, $p > 0.05$). Ten replicates (10 eggs per replicate) were maintained

which the lethal effect on the eggs was highest among the tested blue light wavelengths, showed 96.5% mortality even at a low photon flux density of 1.5×10^{18} photons·m^{-2}·s^{-1}. The lethal effect of 408-nm blue light on the eggs was also relatively high at low photon flux density, showing 78.8% mortality. The lethal effect of 378-nm UVA was higher than that of any blue light wavelength, showing 100% mortality even at 1.5×10^{18} photons·m^{-2}·s^{-1}.

Lethal effect of blue-light irradiation on *L. bostrychophila* adults

Continuous irradiation with 378–494-nm light at 5×10^{18} photons·m^{-2}·s^{-1} significantly increased booklouse adult mortality compared with the control (DD) mortality ($p < 0.05$) (Fig. 2). More precisely, 378–440-nm and 462-nm light showed 96%–100% mortality at this photon flux density. In contrast, irradiation with 508-nm light did not show a significant lethal effect. Irradiation with 378, 408, 420, 456, and 462-nm light showed significant lethal effects, even at 3×10^{18} photons·m^{-2}·s^{-1} ($p < 0.05$). Irradiation with 378 and 408-nm light notably exhibited strong lethal effects, showing 100% and 87% mortality, respectively, at this photon flux density.

Discussion

Liposcelis bostrychophila is a common domestic pest of stored food products that can cause serious damage to products (Turner 1994). In food processing and storage facilities, insecticides cannot often be used because of the risk of contamination of the food products. In addition, the rapid development of chemical resistance by *L. bostrychophila* has also been reported (Huang et al. 2009; Wang et al. 2004). Because *L. bostrychophila* is difficult to control using conventional methods, alternative approaches are expected to be developed (Diaz-Montano et al. 2014). Attractants and light attractions have been studied for the development of traps or lures as an alternative approach (Diaz-Montano et al. 2014, 2016; Green and Turner 2005). However, these control methods can be incorporated into integrated pest management for monitoring this pest (Diaz-Montano et al. 2014) but cannot directly kill them. However, the lethal effect of blue light can be useful as a direct killing method for this pest. In previous papers, we reported that photon flux densities of 3.0×10^{18}, 15.0×10^{18}, and 10.0×10^{18} photons·m^{-2}·s^{-1} are effective in killing *D. melanogaster*, *G. grisescens*, and *C. pipiens* f. *molestus*, respectively. The results obtained in this study show that *L. bostrychophila* eggs can be killed by blue-light irradiation at a relatively low photon flux density, that is, 1.5×10^{18} photons·m^{-2}·s^{-1}, in comparison with that used to kill the above-mentioned pests. It is relatively easy to irradiate the inside of equipment, such

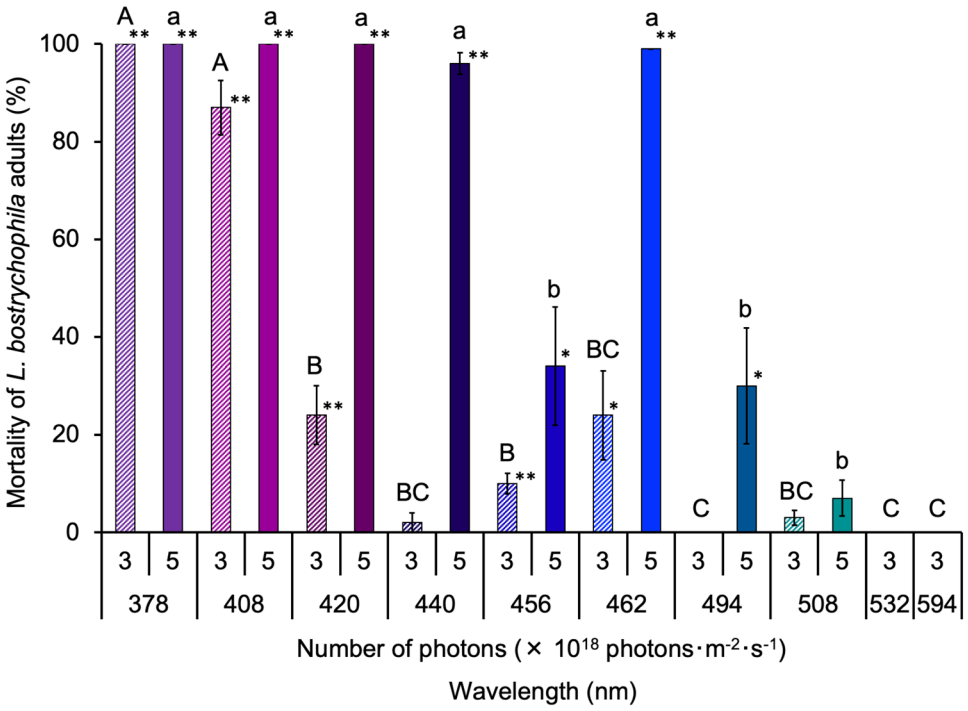

Fig. 2 Comparison of the lethal effects of light irradiation on *Liposcelis bostrychophila* adults using various wavelengths of light. Data represent the means ± standard errors. Mortality rates in treatments (irradiation) were corrected using Abbott's formula (Abbott 1925). Asterisks above the bars indicate significant differences between the treatments and control (DD) (Steel test: * $p < 0.05$, ** $p < 0.01$). No adult died under DD. Bars with the same letters are not significantly different among the wavelengths (Steel–Dwass test, $p > 0.05$). Ten replicates (10 adults per replicate) were maintained

as food processing machines and switchboards, with blue light at this photon flux density. We have developed an LED device that can irradiate ~ 50 cm square space with 470-nm blue light at more than 5.0×10^{18} photons·m^{-2}·s^{-1}, to kill small bugs such as *D. melanogaster* (Hori 2018). This device has already been commercialized and is used in a number of food processing and storage facilities in Japan. It is likely that the occurrence of *L. bostrychophila* inside the above-mentioned equipment can be prevented using this device.

In previous studies, we demonstrated the lethal effect of blue light on several species of insects, including *D. melanogaster* and *T. confusum* (Hori et al. 2014), *G. grisescens* (Hori and Suzuki 2017), *C. pipiens* f. *molestus* (Taniyama et al. 2021), and *A. albopictus* (Taniyama and Hori 2022). Although these previously studied insects are holometabolous, we revealed for the first time that blue-light irradiation is also lethal to hemimetabolous insects in this study; that is, it is thought that blue-light irradiation is lethal to various species of insects, regardless of the type of metamorphosis.

Currently, we are investigating the mechanisms underlying the lethal effects of blue light in insects. In a previous study, we reported that the amount of H_2O_2, a reactive oxygen species (ROS), in the whole body of *Drosophila* pupae was increased by blue light irradiation (Shibuya et al. 2018). In addition, we confirmed that the growth of cultivated cells of *Drosophila* embryos was suppressed by blue-light irradiation. Furthermore, we revealed that the highly toxic blue light wavelengths are species- and growth stage-specific in insects (Hori et al. 2014; Shibuya et al. 2018). Therefore, we hypothesized that the ROS produced by the absorption of specific blue light wavelengths in insect tissues damage them, thereby killing the insects. Kam et al. (2021) reported that 420-nm blue-light irradiation has a negative effect on the function of mitochondria, which specifically absorbs this wavelength because of the presence of porphyrins, and reduces the climbing mobility of adult *Drosophila*. In the current study, the effective lethal wavelength for *L. bostrychophila* eggs had two peaks at 420 and 462 nm in the blue light region. Therefore, under irradiation at ~ 420 nm, lethal effects may result from mitochondrial damage. However, the lethal effect of 408-nm light on adults was higher than that of 420-nm light; additionally, the lethal effect of 462-nm light on eggs and adults was relatively high. Therefore, damage to other sites besides the mitochondria, which absorb 408 and 462-nm blue lights, may have induced the lethal effect on *L. bostrychophila*. Currently, we are investigating the above absorption sites.

In conclusion, blue light irradiation is a safe and clean technique for killing insect pests. The lethal effect of blue light on insects infesting stored food products is evident in this study. Thus, blue light irradiation could be a useful tool in the integrated pest management of food processing and storage facilities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13355-022-00814-5.

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Author contributions MH conceived the study, designed the experiments, and wrote the manuscript. NO performed the experiments. MH and NO analyzed the data.

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Data Availability The datasets are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical approval Not applicable.

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