doi:10.20944/preprints201905.0014.v1

Phototactic response of the oriental armyworm, *Mythimna separata* (Lepidoptera: Noctuidae), to light-emitting diode lights of different wavelengths

Kil-Nam Kim[1,2], Hye-Sung Song[2] , Ryong-Jin Choe[2], Zhi-Juan Huang[1], Qiu-Ying Huang[1,*], Chao-Liang Lei[1,*]

[1] Hubei Insect Resources Utilization and Sustainable Pest Management Key Laboratory, College of Plant Science and Technology, Huazhong Agricultural University, Wuhan, Hubei 430070, China; qyhuang2006@mail.hzau.edu.cn

[2] Institute for Biodiversity, State Academy of Sciences, Pyongyang 00850, Democratic People's Republic of Korea; evertreekkn@163.com

[*] Corresponding author, e-mail: qyhuang2006@mail.hzau.edu.cn (Q. Huang) and ioir@mail.hzau.edu.cn (C. Lei)

Abstract

Recently, light traps using light-emitting diode (LED) lights have been applied to monitor or control insect pests. The oriental armyworm, *Mythimna separata* Walker, is an important insect pest that has caused damage to several cereal crops, including corn, wheat and rice. The present study aims to seek out a sensitive wavelength causing high phototactic response in *M. separata*. The study evaluated the phototactic responses of *M. separata* moths to several LED lights of different wavelengths and luminance intensities under laboratory condition. Results showed that green (520 nm) LED light resulted in significant phototactic response of *M. separata* moths compared to LED lights of other wavelengths. Additionally, the highest attraction rate of the moths to green LED light appeared in luminance intensity group of 200 lux compared to the other intensities groups. Experiments under optimum conditions based on the above experiments revealed that the green LED light exhibited the strongest attraction rate (64.44%) among all experimental groups. An experiment performed in a net cage also showed that green LED light resulted in the highest phototactic response of *M. separata* moths, 1.7 times more than a commercial black light used as control. These findings clearly demonstrate that *M. separata* moths have a high sensitivity to the green LED light. Therefore, a light trap equipped with green LED light could be useful for monitoring and controlling *M. separata* moths.

Key words: phototactic response; *Mythimna separata*; LED; wavelength; attraction rate; luminance intensity; sensitivity

1. Introduction

The oriental armyworm, *Mythimna* (or *Leucania*) *separata* Walker (Lepidoptera: Noctuidae), is an important long-migratory pest in eastern Asia, including the Korean peninsula, China and Japan, and causes damage to several cereal crops, such as corn, wheat and rice; in addition to these major crops, the pest has damaged more than 300 kinds of agricultural and industrial plants in nearly 100 families, thus causing substantial crop production losses annually [1-7]. Widespread outbreaks of *M. separata* are related to climate change, especially increases in temperature [8]. The conventional control of this insect pest depends on synthetic chemical insecticides. However, the excessive use of the chemical insecticides has resulted in problems, such as resistance of the pest to the chemical insecticides, harm to users and eco-system pollution [9,10]. Recently, there has been increasing pressure to search for safe and more efficient alternative pest control methods for the management of *M. separata* [7].

Many insects have a phototactic behavior to an artificial light at night. Therefore, light traps have been widely applied to management of agriculture and forest insect pests having phototaxis. Pest control by use of light traps, which does not negatively impact eco-system conservation and human health, could be an alternative technique used for controlling insect pests in modern organic agriculture [11,12]. In recent years, light traps equipped with light-emitting diode (LED) lights, as the light source, have been applied to monitor or control insect pests [13-15]. LED lights have some benefits, including low electricity consumption, the ability to selectively emit wavelengths, the adjustability of light intensity, high emitting effect, long use time, high mechanical stability, small size and low weight

[13,16]. During the last decade, some studies determined the wavelengths of LED lights that strongly attract some insect pests for using as light sources in light traps for these insect pests [17].

Llight sensitivities of insects vary in responses to different wavelength lights. In addition, the insect's phototactic behavior is influenced by several factors, such as luminance intensity, light exposure time, insect physiological status, temperature, relative humidity, wind direction and wind strength [11,18,19]. Some studies have shown that some insect pests are more sensitive to certain wavelengths of LED light sources. The spiraling whitefly, *Aleurodicus dispersus* Russell (Hemiptera: Aleyrodidae), was most sensitive to violet (405 nm) light emitted by LED light [15]. The cigarette beetle, *Lasioderma serricorne* Fabricius (Coleoptera: Anobiidae), was most sensitive to ultraviolet (UV 373 nm) and blue (470 nm) LED lights [20]. Green (526 nm) LED light yielded the most phototactic responses from the whitefly species, *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) and *Trialeurodes vaporariorum* Westwood (Hemiptera: Aleyrodidae) [21]. The Indian meal moth, *Plodia interpunctella* Hübner (Lepidoptera: Pyralidae), was most attracted to ultraviolet (UV 395 nm) LED light [22]. Thus, the insect phototactic responses represent a priority research topic in the promotion of physical pest control.

There have been few studies on the phototactic response of *M. separata* moths to light sources, especially *M. separata* responses to specific wavelengths and light intensities. The present study aimed to find a sensitive wavelength causing a strong phototactic behavior in *M. separata* moths. We evaluated the phototactic response levels of *M. separata* moths to several wavelengths, luminance intensities, and light exposure times by using LED lights and a Y-maze bioassay chamber under laboratory condition. Then, the study reevaluated the phototactic responses of *M. separata* moths under the optimum conditions (luminance intensities and exposure times) determined by our earlier experiments. Finally, we evaluated some of the above the experimental results within a net cage condition. Our findings may provide a theoretical and scientific basis for improving the light trap technique in physical pest control of *M. separata* moths.

2. Materials and methods

2.1 Experimental insects

Adults of the experimental insect, *M. separata*, were reared at the temperature 25±3°C, with 65±10% relative humidity (RH) and a light: dark photoperiod of 14 h: 10 h in an insect rearing room. We used an artificial diet described by Bi [23] for larvae and 10 % honeybee water was used as adult’s diet. During the rearing period, all insects were maintained with no exposure to any chemicals. Only three-day-old *M. separata* moths were used for the phototactic response experiments.

2.2 Y-maze bioassay chamber

To assessing the phototactic behavioral responses of *M. separata* moths, Y-maze bioassay chambers designed by Kim et al. [9] were employed in the experiments under laboratory. The Y-maze phototactic bioassay chamber consisted of an opaque acrylic body (20×20×100 cm)，and two transparent acrylic walls were situated at both sides of the light side area and the dark side area above the bioassay chamber to enable the observation of the insect behavior. An insect entrance hole was located in the upper center of the insect resource box, and nylon netting covered the outer light side area to prevent experimental insects from escaping. The light source was installed on opposite side of light side area in the Y-maze chamber.

2.3 Light sources and luminance intensity measurement tool

The LED lights (5 W) used for the experiment were measured by using a spectrometer (USB4H11915; Ocean Optics Co. Ltd., USA), the wavelengths and the light irradiances of these LED lights are displayed in Table 1. The phototactic responses of *M. separata* under optimum experimental conditions and the net cage condition were compared with those under commercial black light (365±7 nm; 18 W), which served as the control. All of the LED lights and black lights were purchased from Shenzhen New Photoelectric Technology Co. Ltd., China. The luminance intensity (lux) of LED lights was measured by using a digital lux meter (GM1020-CH-00; Shenzhen Jumaoyuan Science and Technology Co. Ltd., China) at the established point in the center of light side area within the Y-maze chamber.

2.4 Experiment in the laboratory

The phototactic responses of *M. separata* to LED lights were evaluated in the Y-maze chamber under different wavelengths, luminance intensities, and light exposure times, based on the experimental method described by Kim et al. [9]. Prior to the experiment, the insect resource area was closed by boards separating the light side and the dark side. Each experiment group contained 30 robust three-day-old moths (15 males and 15 females). These moths were moved through the insect entrance hole into insect source box of the Y-maze chamber and were maintained in the dark for two hours. Every experiment was started at 8:00 P.M.; while darkness was maintained at the dark side of the Y-maze chamber, LED light were irradiated at the light side of the chamber. After LED light was turned on, both of the separating boards were removed from the Y-maze chamber.

The phototactic response of the *M. separata* moths was determined based on the number of insects attracted to the light side. The attraction rate was calculated with the following equation: attraction rate (%) = (number of insects attracted in the "light side") / (30 insects) × 100%. Each experiment was executed for one hour and was observed every 10 minutes. So, the exposure time indicates from the time turning on the light source to the observing time. To estimate a significant effect between several light sources causing high phototactic behavioral responses, we produced the optimum conditions (e.g., intensity and exposure time) according to each LED light source, which result in a strong phototactic behavior of the moths, based on the above conducted experiments, and reevaluated the phototactic behavioral responses to different light sources under the optimum conditions. After each experiment, the light and dark positions were switched in the chamber. Every experiment was carried out at a temperature 25±3°C, with 65±10% relative humidity (RH) in the darkness. There were three replicates for each experiment.

2. 5 Experiment in the net cage

An oblong net cage 10 m long, 10 m wide and 4 m high was covered with nylon net cloth. The net cage was installed outdoors in the field; thus the darkness of the cage depended on the darkness of the outdoor condition after sunset. Two (450 nm and 520 nm wavelength) LED lights (5 W) and a commercial black light (365±7 nm; 18 W) were installed inside the cage. The distance between the lights was 3 m, and the height of each light was 1 m. Three infrared cameras were set 70 centimeters in front of each light at the same height as the light sources. Each experimental group included 200 robust *M. separata* moths, which were released 5 hours before the experiment started in the cage. Each experiment started at 8:30 P.M. and lasted two hours, and the experiments were conducted from 15 to 25 September, 2018. The phototactic response of the *M. separata* moths was evaluated by counting the number of times they appeared in videos of each experiment. The videos of each experiment were observed for 10-minute intervals, and the total number of appearances of the moths over a two-hour period was determined. The experiment in the net cage was replicated five times.

2.6 Statistical analysis

We performed one-way analysis of variance (ANOVA) with the software SPSS (SPSS Inc., Chicago, IL, USA) to compare the attraction rates of *M. separata* moths to several light sources. Values are expressed as the means and standard errors (mean±SEM). Significant differences were analyzed using Tukey's HSD test (P <0.05).

3. Results

3.1 Phototactic response of M. separata moths to LED lights of different wavelengths under several luminance intensities

The phototactic responses of *M. separata* moths to LED lights of different wavelengths (two ultraviolet LED lights, six LED lights with visual wavelengths and one white LED light) were evaluated under luminance intensities of 50 lux, 100 lux, 150 lux and 200 lux, respectively (Figure 1). The violet (400 nm), ultraviolet (UV 385 nm), green (520 nm) and white (420-650nm) LED lights under a luminance intensity of 50 lux revealed high attraction rates (average attraction rates of 52.02%, 49.99%, 50.37%, and 52.35%, respectively) (Figure 1a). Additionally, the high attraction rates of the *M. separata* moths to the LED lights almost all appeared by an exposure time of 30 min or 40 min. So, attraction rates of the moths to different LED lights were assessed when the moths were exposed to different LED lights for 40 min (Figure 2). Under a luminance intensity of 50 lux, significant increases in the attraction rates over exposure time, up to 40 min, were observed for violet (400 nm), ultraviolet (385 nm), green (520 nm) and white (420-650 nm) LED lights, with attraction rate of 57.31%, 54.52%, 53.91% and 53.49%, respectively (Figure 2a). No significant difference was observed among these four kinds of LED lights, but a significant difference was found between these lights and the red (625 nm) LED light (F=4.676; df=8, 18; P=0.003). High attraction rates of *M. separata* moths under a luminance intensity of 100 lux were observed for the green (520 nm), blue (450 nm) and yellow (590 nm) LED lights, with average attraction rate of 54.44%, 51.11% and 48.89%, respectively (Figure 1b). The green (520 nm), yellow (590 nm), and blue (450 nm) LED lights under a luminance intensity of 100 lux and an exposure time of 40 min resulted in higher phototactic responses (attraction rates of 55.56%, 52.22%, and 51.11%, respectively) than the other wavelength LED lights, and the differences were significant compared to ultraviolet (365 nm) wavelength (F=2.695; df=8, 18; P=0.038) (Figure 2b).

Meanwhile, the green (520 nm) and blue (450 nm) LED lights with a luminance intensity of 150 lux yielded higher phototactic responses from *M. separata* moths (average attraction rates of 59.09% and 56.81% respectively) than the other LED light groups (Figure 1c).

When *M. separata* moths were exposed to LED lights of different wavelengths under a luminance intensity of 150 lux for an exposure time of 40 min, significant increases in the attraction rates were recorded for the green (520 nm) and blue (450 nm) LED lights (attraction rates of 59.14% and 58.53% respectively) compared to two ultraviolet (365 nm and 385 nm), violet (400 nm) and dark red (680 nm) LED lights, but there were no significant differences compared to the other wavelength LED lights (*F*=7.529; *df*=8, 18; *P*=0.001) (Figure 2c). The highest significant increase in the average attraction rates of *M. separata* moths under a luminance intensity of 200 lux was observed for the green (520 nm) wavelength (average attraction rate of 59.32%) (Figure 1d). Furthermore, the high attraction rates of the moths recorded for the green (520 nm) LED light after an exposure time of 30 min. A significant increase in the attraction rates of *M. separata* moths to nine wavelength LED lights under a luminance intensity of 200 lux and an exposure time of 40 min was only found for the green (520nm) LED light (*F*=12.907; *df*=8, 18; *P*=0.000) (Figure 2d). Moreover, the attraction rate to the green LED light was the highest, with a value of 63.65%. Additionally, the attraction rates to ultraviolet (365 nm), violet (400 nm), yellow (590 nm) and white LED lights were significantly higher than that to the ultraviolet (385 nm) LED light, but those to blue (450 nm), red (625 nm) and dark red (680 nm) LED lights was no a significant difference compared to that of ultraviolet (385 nm) LED light.

3.2 Effect of luminance intensity on the phototactic response of M. separata moths to green (520 nm) LED light

Effect of the luminance intensity on the phototactic response of *M. separata* to green LED light was evaluated under several luminance intensities with an exposing time of 40 min

(Figure 3). The attraction rate of the moths exposed to the green (520nm) LED light under a luminance intensity of 200 lux was significantly higher than that under a luminance intensity of 250 lux, but no significant difference was observed among the other intensities (*F*=3.417; *df*=4, 10; *P*=0.038).

3.3 Phototactic response of M. separata moths under the optimum conditions of each LED light

Phototactic responses of the *M. separata* moths to LED lights of ten wavelengths under these optimum conditions which produced by the above experimental results were reevaluated and compared to the response to a commercial black light used as a control (Table 2). In this experiment, the green (520 nm) LED light under optimum condition (luminance intensity of 200 lux and exposure time of 40 min) resulted in the highest attraction rate, with 64.44%. Moreover, it was 1.38 times more attractive than control (black light; 46.67%). The number of moths attracted to the light side of the green LED light was significantly higher than those of the other LED lights and control (*F*=5.408; *df*=10, 22; *P*=0.001). A significant difference in the dark side was recorded between two LED lights (590 nm and 625 nm) and the other LED lights (*F*=5.035; *df*=10, 22; *P*=0.001); however, there were no significant differences relative to the control. The ratio of moth’s numbers in the light side and the dark side was the highest for the green LED light among all the experimental groups and control.

3.4 Phototactic response of M. separata moths under the net cage condition

The attraction effect of *M. separata* moths to blue (450 nm) and green (520 nm) LED lights compared with a commercial black light as a control in the net cage was evaluated (Figure 4). A significant increase in the number of *M. separata* moths that appeared in front of the light source for two hours was recorded for green (520 nm) LED light compared with the other lights, and was 1.7 times higher than the number of moths attracted to the black light as the control (F=74.524; df=2, 12; P=0.001). However, a significant decrease was recorded for the blue (450 nm) LED light, which had an even lower number than the control. We analyzed the phototactic response tendencies of *M. separata* moths to different light sources based on observations 10-minute intervals for two hours in the net cage (Figure 5). The phototactic responses of the moths to three light sources in the net cage showed many complicated peaks in the time series. However, a higher rate of phototactic responses occurred for the green LED light compared with the other lights. Additionally, relatively high attraction effects were recorded after the illumination exposure time of 30 min, and again decreased after 110 minutes.

4. Discussion

Many insects exhibit phototactic behaviors, such as positive phototaxis (attraction to light sources) or negative phototaxis (repelled by light sources). The wavelengths of light sources causing the phototactic behavior are species-specific in insects. Furthermore, the phototactic response level is influenced by the wavelength, luminance intensity and exposure time of the light source [17,24,25].

Our results confirmed that the phototactic response level of *M. separata* moths depends on the specific wavelength, luminance intensity and exposure time of the light source. Some studies have evaluated the phototactic responses of several species in the

Lepidoptera to different LED light wavelengths. The attraction rate of the tobacco cutworm, *Spodoptera litura*, to green (520±5 nm) high-powered LEDs under 40 lux and an exposure time of 60 min was highest than those to other wavelengths [26]. The Indian meal moth, *P. interpunctella* has the most sensitivity to violet (405 nm) LEDs based on an electroretinogram recording test and behavior experiment [27]. However, in other study, *P. interpunctella* moths were most attracted to green (520±5 nm) LEDs under 60 lux and an exposure time of 30 min [28]. In addition, the oriental fruit moth, *Grapholita molesta* was significantly more attracted to violet (405 nm) and green (540 nm) LEDs [29]. The diamondback moth, *Plutella xylostella*, moths were significantly more attracted to green (520±5 nm) LED than other LEDs [30].

Our experimental results are similar to the results of these previous studies. When *M. separata* moths were exposed to LED lights under a luminance intensity of 50 lux, these moths preferred the violet (400 nm) LED light. However, under luminance intensities of 100 lux to 200 lux, the moths were more attracted to the green (520 nm) LED light compared with the other LED lights. Additionally, the results of the phototactic response experiments with *M. separata* moths exposed to the optimum conditions for each LED light showed that the green (520 nm) LED light resulted in the highest attraction rate. Moreover, the experimental data in the net cage condition also was similar with the results in the laboratory.

Most insects have three types of photoreceptors that are sensitive to UV, blue and green wavelength ranges, which is generally the case for pest moths [27,31,32]. A study on the relation between light source of specific wavelength and the quantity of insects caught by a light trap equipped with the light source have found that light sources of green wavelength and UV attract more individuals of the Lepidoptera than the light sources of other wavelengths, suggesting that this phenomena may be related to structure and function of compound eyes of insects [33]. Some studies reported that the 75 % photoreceptors were related with green sensitivity, and the other photoreceptors were related to UV and blue sensitivities in the tobacco hornworm (*Manduca sexta*) [34,35]. While, the beet armyworm (*Spodoptera exigua*) moths with *Se-lw* (opsin gene related to green photoreceptor) knocked down exhibited decreased phototactic behavior, suggesting that the green receptors play more critical role in the photosensitivity to an artificial light than other photoreceptors [36]. Based on our results, *M. separata* moths demonstrate the highest sensitivity to the green wavelength, which may be due to the green photoreceptor in their compound eyes.

Attraction effect of insects may vary depending on oxidant stress level that a light source induces in the insects. One study explored the relationship between the quantities of underground pests caught by traps with light sources of different wavelengths and the oxidant stress levels of the pests exposed to these light sources; that study found that a trap equipped with a light source resulting in a weaker oxidative stress can attract more ground pests, such as cockchafers [19]. The some studies reported that the oxidative stress level in the *M. separata* moths under a green (520 nm) light was weak but was strong under UV irradiation [37,38]. Therefore, *M. separata* moths may have a stronger phototactic behavior to the green light than lights of other wavelengths. However, more scientific evidence is needed to verify whether the phototactic behavior of the insects is passively produced by the light stress.

Color vision of many animals, including insects, aids them in locating their habitat, to seek food or mates, and to avoid their enemies and rivals [39]. For example, phytophagous insects are sensitive to any wavelengths reflecting from host plants within the range of 500 to 580 nm. Based on visual stimuli, insects can find host plants by cooperating with plant volatile chemical information [40,41]. Based on the suggestions of previous data, *M. separata* moths may be indiscriminately attracted to light or color of green wavelength range emitted by objects including non-host plants. The high attraction of *M. separata* moths to violet (which has a wavelength between that of ultraviolet light and that of visual light) LED light under a luminance intensity of 50 lux may be related to the ultraviolet photoreceptor in the compound eyes of the insect. Moreover *M. separata* moths under low luminance intensity may be more sensitive to short wavelengths.

Phtotactic response level to a light source in the same insect species is different from luminance intensity of the light source [17,42]. Luminance intensity causing a high attraction rate to a green light source in *S. litura* and *P. interpunctella* moths was 40 lux and 60 lux, respectively [26,28]. In our results, the phototactic response level of *M. separata* moths to green LED light gradually increased with the luminance intensity from 50 lux to 200 lux, but the phototactic response level of the moths decreased under a luminance intensity of 250 lux. Similarly, previous studies have revealed that low luminance intensities result in an increased phototactic response of insects, but high light intensities result in a decreased phototactic response of insects [42,43]. Our results showed that the phototactic behavior of *M. seaprata* moths also demonstrated luminance intensity preferences, suggesting that 200 lux in green (520 nm) wavelength range is the optimum luminance intensity for these insects.

Our finding supports previous studies that insects can detect monochrome wavelengths and luminance intensities with different sensitivities and may provide a theoretical and scientific basis for improving the light trap technique for *M. separata* moths.

5. Conclusion

Many insects, including moths, are attracted to artificial light, because insects have phototactic behavioral characteristic, but their phototactic response level and sensitivity to light wavelengths varies among species. The present research revealed that *M. separata* moths demonstrated the highest phototactic response to green (520 nm) LED light compared to the other wavelength LED lights under laboratory and net cage conditions. Our finding shows that the moths can detect monochromatic wavelengths and luminance intensities. Consequently, LED light of green wavelength (520 nm) could be used as light source in the light trap for monitoring and controlling *M. separata* moths. In addition, the possibility of employing traps equipped with LED lights of specific wavelengths to control insect pest moths may be worthy of further investigation.

Author Contributions:

K.N.K., Q.Y.H. and C.L.L. designed this study. K.N.K., H.S.S. and Z.J.H. performed the experiments under the lab and net setup, K.N.K. and R.J.C. analyzed the experimental data. The article was written by K.N.K. and Q.Y.H. in consultation with all authors.

Funding:

This study was funded by the National Key Research and Development Program of China (2017YFD0200900) and the National Natural Science Foundation of China (31871958).

References

1. Sharma, H.C.; Davies, J.C. The oriental armyworm, *Mythimna separata* (Walker). Distribution, biology and control: a literature review. Miscellaneous Reports(59). *Centre for Overseas Pest Research (UK)* **1983,** *59*, 1-24.

2. Sharma, H.C.; Sullivan, D.J.; Bhatnagar, V.S. Population dynamics and natural mortality factors of the oriental armyworm, *Mythimna separata* (Lepidoptera: Noctuidae), in south-central india. *Crop Prot.* **2002**, *21*, 721-732.

3. Chen, R.L.; Bao, X.Z.; Drake, V.A.; Farrow, R.A.; Wang, S.Y.; Sun, Y.J.; Zhai, B.P. Radar observations of the spring migration into northeastern China of the oriental armyworm moth, *Mythimna separata*, and other insects. *Ecol. Entomol.* **2010**, *14*, 149-162.

4. Jiang, X.; Luo, L.; Zhang, L.; Sappington, T.W.; Hu, Y. Regulation of migration in *Mythimna separata* (Walker) in china: A review integrating environmental, physiological, hormonal, genetic, and molecular factors. *Environ. Entomol.* **2011**, *40*, 516-533.

5. Jung, J.K.; Seo, B.Y.; Cho, J.R.; Kim, Y. Monitoring of *Mythimna separata* adults by using a remote-sensing sex pheromone trap. *Korean J Appl Entomol* **2013**, *52*, 341-348.

6. Liu, Y.; Qi, M.; Chi, Y.; Wuriyanghan, H. De novo assembly of the transcriptome for oriental armyworm *Mythimna separata* (Lepidoptera: Noctuidae) and analysis on insecticide resistance-related genes. *J. Insect Sci.* **2016**, *16(92)*, 1-8.

7. Lihuang, K.M.; Zhang, Z.; Kim, K.N.; Huang, Q.Y.; Lei, C.L. Antennal and behavioral responses of *Mythimna separata* (Walker) to three plant volatiles. *Environ. Sci. Pollut. Res.* **2017**, *24*, 24953-24964.

8. Zhao, Z.; Sandhu, H.S.; Ouyang, F.; Ge, F. Landscape changes have greater effects than climate changes on six insect pests in China. *Sci. China Life Sci.* **2016**, *59*, 627-633.

9. Kim, K.N.; Song, H.S.; Li, C.S.; Huang, Q.Y.; Lei, C.L. Effect of several factors on the phototactic response of the oriental armyworm, *Mythimna separata* (Lepidoptera: Noctuidae). *J. Asia-Pac. Entomol.* **2018**, *21*, 952-957.
10. Song, J.; Jeong, E.Y.; Lee, H.S. Phototactic behavior 9: phototactic behavioral response of *Tribolium castaneum* (Herbst) to light-emitting diodes of seven different wavelengths. *J. Appl. Biol. Chem.* **2016**, *59*, 99-102.
11. Jing, X.F.; Lei, C.L. Advances in research on phototaxis of insects and the mechanism. *Entomological Knowledge* **2004**, *41*, 198-203. (In Chinese with English abstract)
12. Shimoda, M.; Honda, K.I. Insect reactions to light and its applications to pest management. *Appl. Entomol. Zool.* **2013**, *48*, 413-421.
13. Tamulaitis, G.; Duchovskis, P.; Bliznikas, Z.; Breive, K.; Ulinskaite, R.; Brazaityte, A.; Novickovas, A.; Zukauskas, A. High-power light-emitting diode based facility for plant cultivation. *J. Phys. D Appl. Phys.* **2005**, *38*, 3182-3187.

14. Cohnstaedt, L.W.; Gillen, J.I.; Munstermann, L.E. Light-emitting diode technology improves insect trapping. *J. Am. Mosq. Control Assoc.* **2008**, *24*, 331-334.
15. Zheng, L.X.; Zheng, Y.; Wu, W.J.; Fu, Y.G. Field evaluation of different wavelengths light-emitting diodes as attractants for adult *Aleurodicus dispersus* Russell (Hemiptera: Aleyrodidae). *Neotrop. Entomol.* **2014**, *43*, 409-414.
16. Yeh, N.; Chung, J.P. High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation. *Renew. Sus. Energ. Rev.* **2009**, *13*, 2175-2180.
17. Park, J.H.; Lee, H.S. Phototactic behavioral response of agricultural insects and stored-product insects to light-emitting diodes (LEDs). *Appl. Biol. Chem.* **2017**, *60*, 137-144.
18. Liao, H.; Shi, L.; Liu, W.; Du, T.; Ma, Y.; Zhou, C.; Deng, J. Effects of light intensity on the flight behaviour of Adult *Tirumala limniace* (Cramer) (Lepidoptera: Nymphalidae: Danainae). *J. Insect Behav.* **2017**, *30*, 139-154
19. Gao, Y.; Li, G.; Li, K.; Lei, C.; Huang, Q. Comparison of the trapping effect and antioxidant enzymatic activities using three different light sources in cockchafers. *Environ. Sci. Pollut. Res.* **2017**, *24*, 27855-27861.
20. Katsuki, M.; Arikawa, K.; Wakakuwa, M.; Omae, Y.; Okada, K.; Sasaki, R.; Shinoda, K.; Miyatake, T. Which wavelength does the cigarette beetle, *Lasioderma serricorne* (Coleoptera: Anobiidae), prefer? Electrophysiological and behavioral studies using light-emitting diodes (LEDs). *Appl. Entomol. Zool.* **2013**, *48*, 547-551.
21. Jahan, S.M.H.; Lee, G.S.; Lee, S.; Lee, K.Y. Acquisition of tomato yellow leaf curl virus enhances attraction of *Bemisia tabaci* to green light emitting diodes. *J. Asia-Pac. Entomol.*

2014, *17*, 79-82.

22. Kishanr, S.; Thomasw, P. Responses of adult *Plodia interpunctella* (Hubner) (Lepidoptera: Pyralidae) to light and combinations of attractants and light. *J. Insect Behav.* **2008**, *21*, 422-439.
23. Be, F.C. A new artificial diet for the army worm *Leucania separata* Walker. *Acta Entomol. Sin.* **1981**, *24*, 379-383. (In Chinese with English abstract)
24. Cloyd, R.A.; Dickinson, A.; Larson, R.A.; Marley, K.A. Phototaxis of fungus gnat, *Bradysia* sp. nr *coprophila* (Lintner) (Diptera: Sciaridae), adults to different light intensities. *Hortscience* **2007**, *42*, 1217-1220.
25. Van, L.F.; Ettema, J.A.; Donners, M.; Wallisdevries, M.F.; Groenendijk, D. Effect of spectral composition of artificial light on the attraction of moths. In *Biol. Conserv.* **2011**, *144*, 2274-2281.
26. Yang, J.Y.; Kim, M.G.; Lee, H.S. Phototactic behavior: Attractive effects of *Spodoptera litura* (Lepidoptera: Noctuidae), tobacco cutworm, to high-power light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* **2012**, *55*, 809-811.
27. Cowan, T.; Gries, G. Ultraviolet and violet light: attractive orientation cues for the Indian meal moth, *Plodiainterpunctella*. *Entomol. Exp. Appl.* **2009**, *131*, 148–158.
28. Park, J.H.; Lee, H.S. Phototactic behavior 10: phototactic behavioral effects of *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae) adults to different light-emitting diodes of seven wavelengths. *J. Appl. Biol. Chem.* **2016**, *59*, 95-98.
29. Sun, Y.X.; Tian, A.; Zhang, X.B.; Zhao, Z.G.; Zhang, Z.W.; Ma, R.Y. Phototaxis of *Grapholitha molesta* (Lepidoptera: Olethreutidae) to different light sources. *J. Econ.*

Entomol. **2014**, *107*, 1792-1799.

30. Cho, K.S.; Lee, H.S. Visual preference of diamondback moth, *Plutella xylostella*, to light-emitting diodes. *J. Korean Soc. Appl. Biol. Chem.* **2012**, *55*, 681-684.
31. Briscoe, A.D.; Chittka, L. The evolution of color vision in insects. *Annu. Rev. Entomol.* **2001**, *46*, 471-510.
32. Diaz-Montano, J.; Campbell, J.F.; Phillips, T.W.; Cohnstaedt, L.W.; Throne, J.E. Evaluation of light attraction for the stored-product psocid, liposcelis bostrychophila. *J. Pest Sci.* **2015**, *89*, 923-930.
33. Jing, X. Nocturnal insects' phototactic behavior to different light and the effects of black light on the enzyme in bollworm, *Helicoverpa armigera*. *Master's Thesis*, Huazhong Agrocultural University, Wuhan, China, **2004.**
34. Cutler, D.; Bennett, R.; Stevenson, R.; White, R. Feeding behavior in the nocturnal moth *Manduca sexta* is mediated mainly by blue receptors, but where are they located in the retina? *J. Exp. Biol.* **1995**, *198*, 1909-1917.
35. White, R.H.; Huihong, X.; Münch, T.A.; Bennett, R.R.; Grable, E.A. The retina of *Manduca sexta:* rhodopsin expression, the mosaic of green-, blue- and UV-sensitive photoreceptors, and regional specialization. *J. Exp. Biol.* **2003**, *206*, 3337-3348.
36. Liu, Y.J.; Yan, S.; Shen, Z.J.; Li, Z.; Zhang, X.F.; Liu, X.M.; Zhang, Q.W.; Liu, X.X. The expression of three opsin genes and phototactic behavior of *Spodoptera exigua* (Lepidoptera: Noctuidae): Evidence for visual function of opsin in phototaxis. *Insect Biochem. Molec. Biol.* **2018**, *96*, 27-35.
37. Ali, A.; Rashid, M.A.; Huang, Q.Y.; Lei, C.L. Influence of UV-A radiation on oxidative

stress and antioxidant enzymes in *Mythimna separata* (Lepidoptera: Noctuidae). *Environ. Science. Pollut. Res.* **2017**, *24*, 8392-8398.

38. Kim, K.N.; Yun, C.N.; Sin, U.C.; Huang, Z.J.; Huang, Q.Y.; Lei, C.L. Green light and light stress in moth: Influence on antioxidant enzymes in the oriental armyworm, *Mythimna separata* (Lepidoptera: Noctuidae). *Environ. Science. Pollut. Res.* **2018**, *25*, 35176-35183.
39. Chen, Z.; Liu, X.; Zhou, J.X.; Dou, H.; Kuang, R.P. Phototactic behaviour of *Pachyneuron aphidis* (Hymenoptera: Pteromalidae) – hyperparasitoid of *Myzus persicae* (Hemiptera: Aphidiae). *Bio. Sci. Techn.* **2014**, *24*, 1469-1480.
40. Couty, A.; Emden, H.V.; Perry, J.N.; Hardie, J.; Pickett, J.A.; Wadhams, L.J. The roles of olfaction and vision in host The roles of olfaction and vision in host - plant finding by the diamondback moth, *Plutella xylostella*. *Physiol. Entomol.* **2006**, *31*, 134–145.
41. Blackmer, J.L.; Byers, J.A.; Cesar, R.S. Evaluation of color traps for monitoring *Lygus* spp.: Design, placement, height, time of day, and non-target effects. *Crop Prot.* **2008**, *27*, 171-181.
42. Wei, G.; Zhang, Q.; Zhou, M.; Wu, W. Studies on the phototaxis of *Helicoverpa armigera* (Hübner). *Acta Biophys. Sin.* **2000**, *16*, 89-95.
43. Chen, Y.; Luo, C.W.; Kuang, R.P.; Li, H.W.; Zheng, C.; Liu, Y.J. Phototactic behavior of the armand pine Phototactic behavior of the armand pine bark weevil, *Pissodes punctatus*. *J. Insect Sci.* **2013**, *13*, 1-10.

Figures

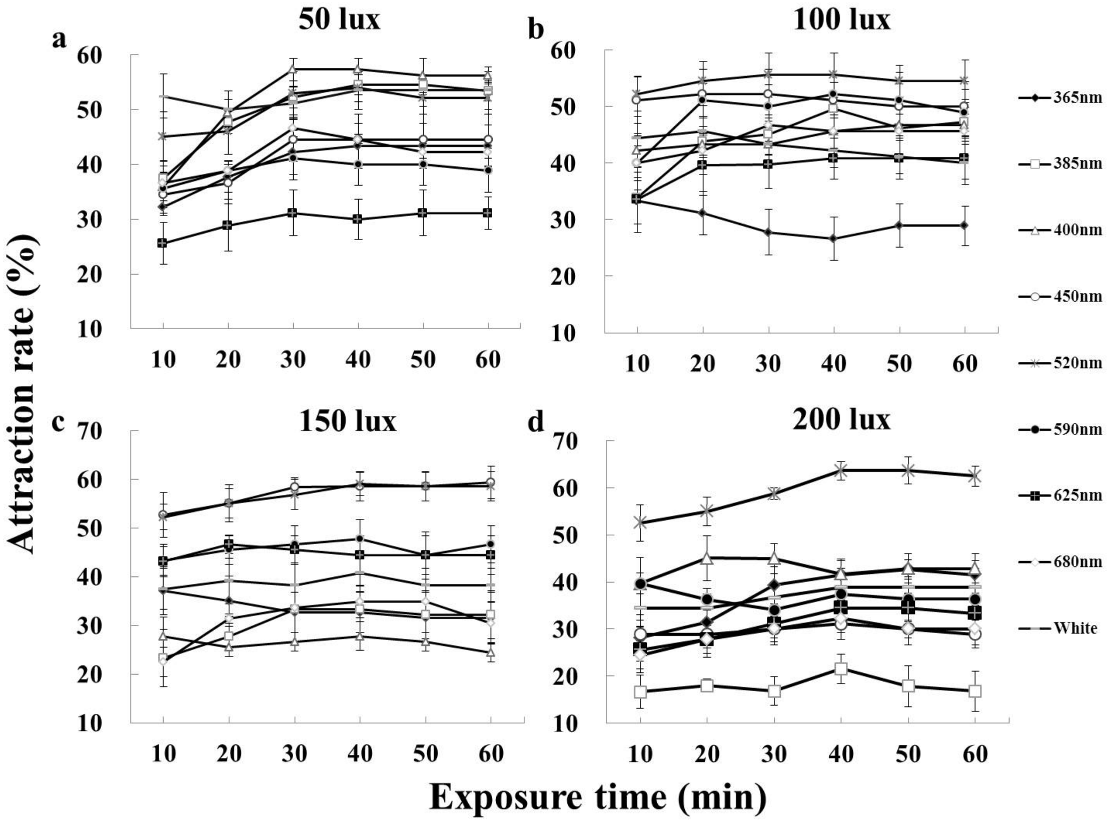

Figure 1. Phototactic responses of *M. separata* moths to LED lights of different wavelengths under several luminance intensities. The values of the points on each line express the mean, and the error bars on the points express the SEM.

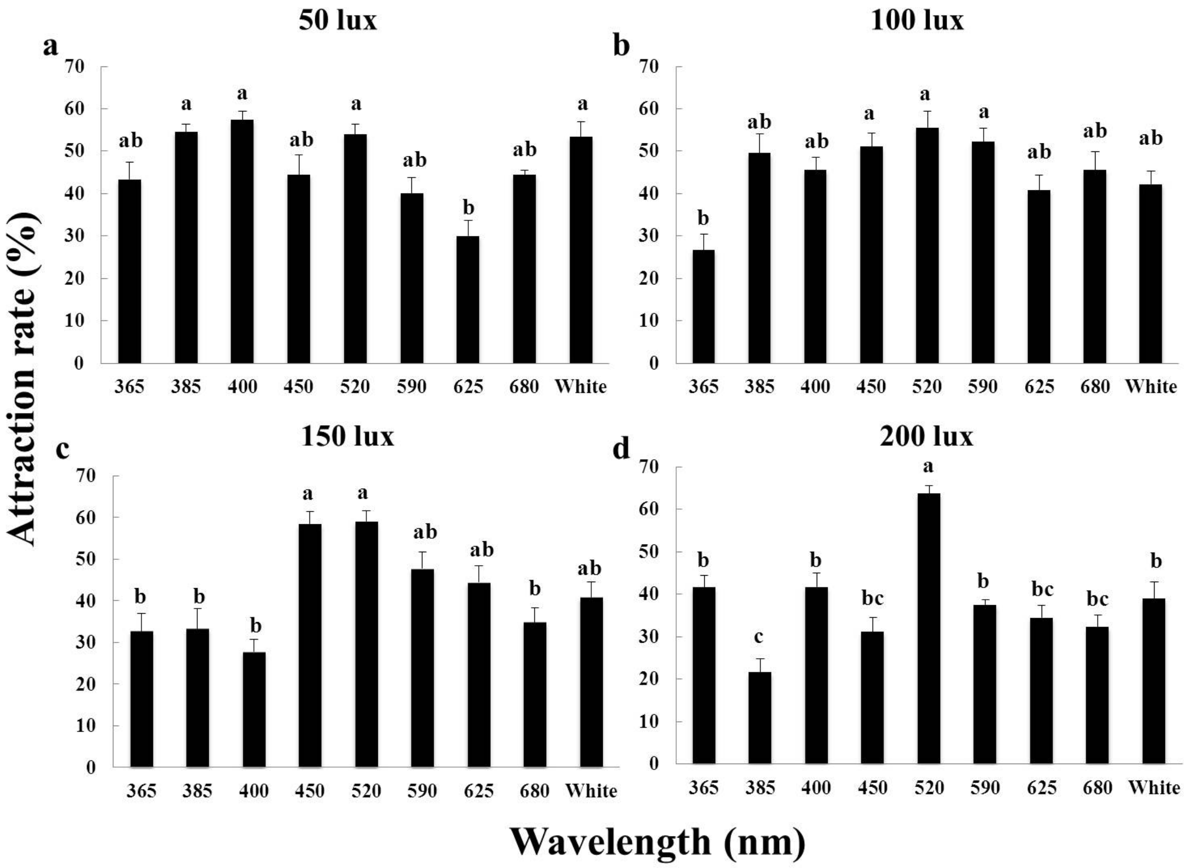

Figure 2. Attraction rate of *M. separata* moths to LED lights of different wavelengths under several luminance intensities with an exposure time of 40 min. The figure was derived from Figure 1. Bars indicate the mean and error bars express the SEM. Different letters above each bar denote significant differences according to the Tukey HSD test (*P*<0.05).

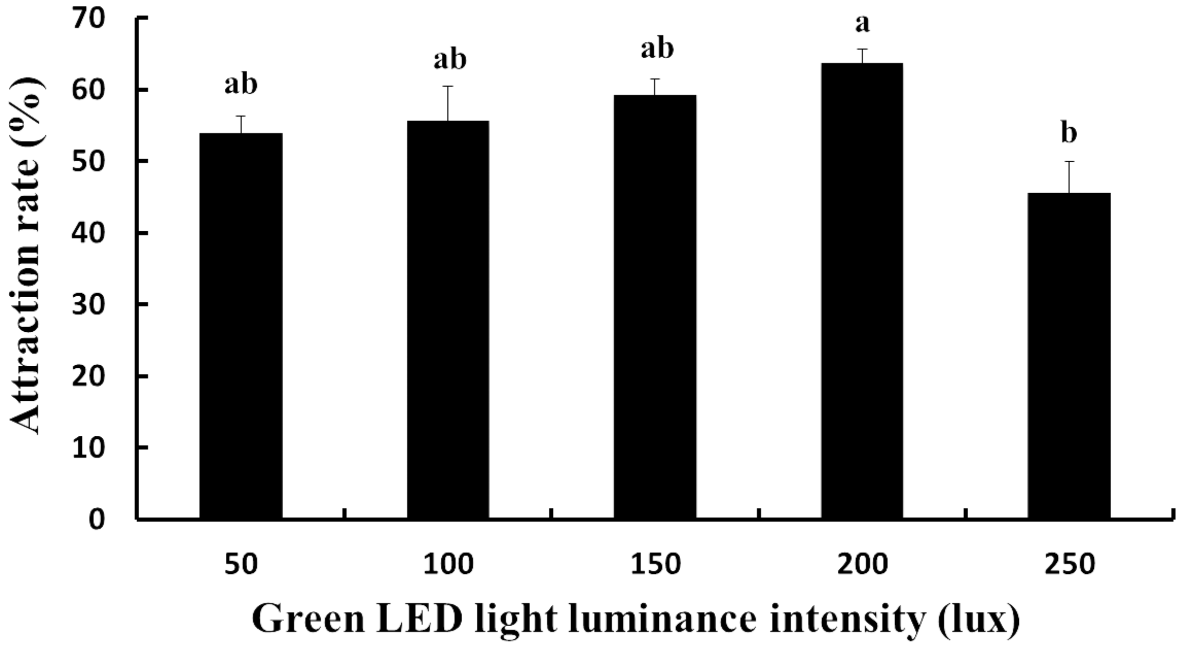

Figure 3. Effect of luminance intensity on the phototactic response of *M. separata* moths exposed to green (520 nm) LED light. Here, the exposure time is 40 min. Bars indicate the means and error bars express the SEM. Different letters denote the significant differences according to the Tukey HSD test (*P*<0.05).

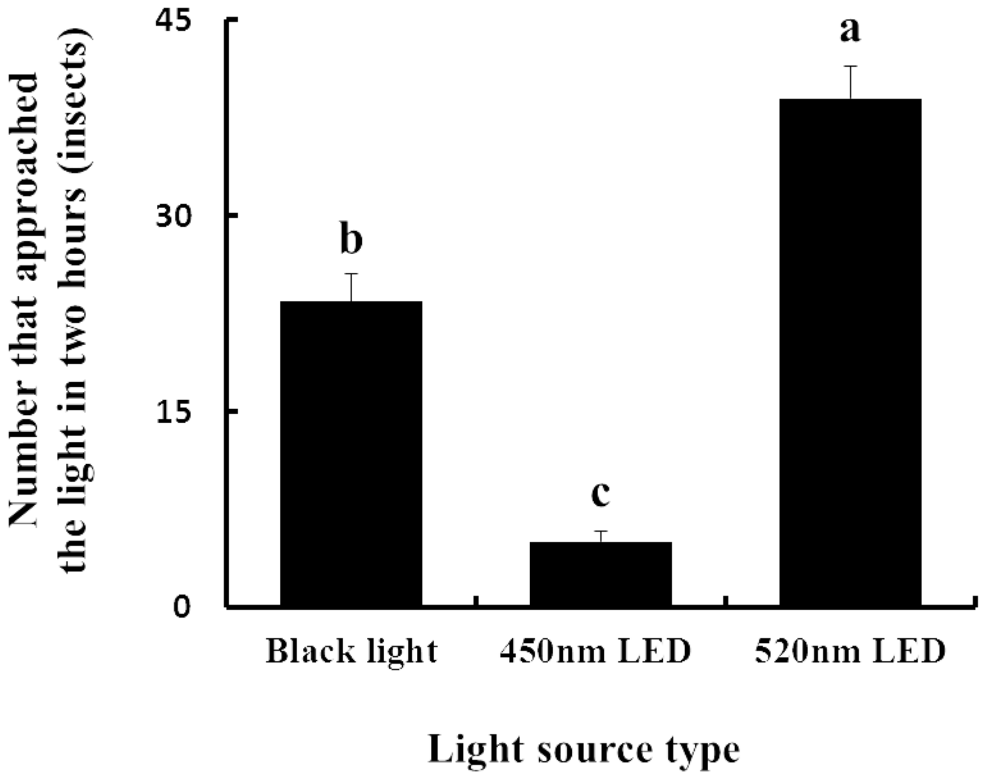

Figure 4. Attraction effects of different light sources on *M. separata* adults in the net cage. The value of each bar indicates the total number of adults that appeared in front of each light over a two hour period, and the error bars indicate the SEM. The different letters above each bar express significant differences according to the Tukey HSD test (*P*<0.05).

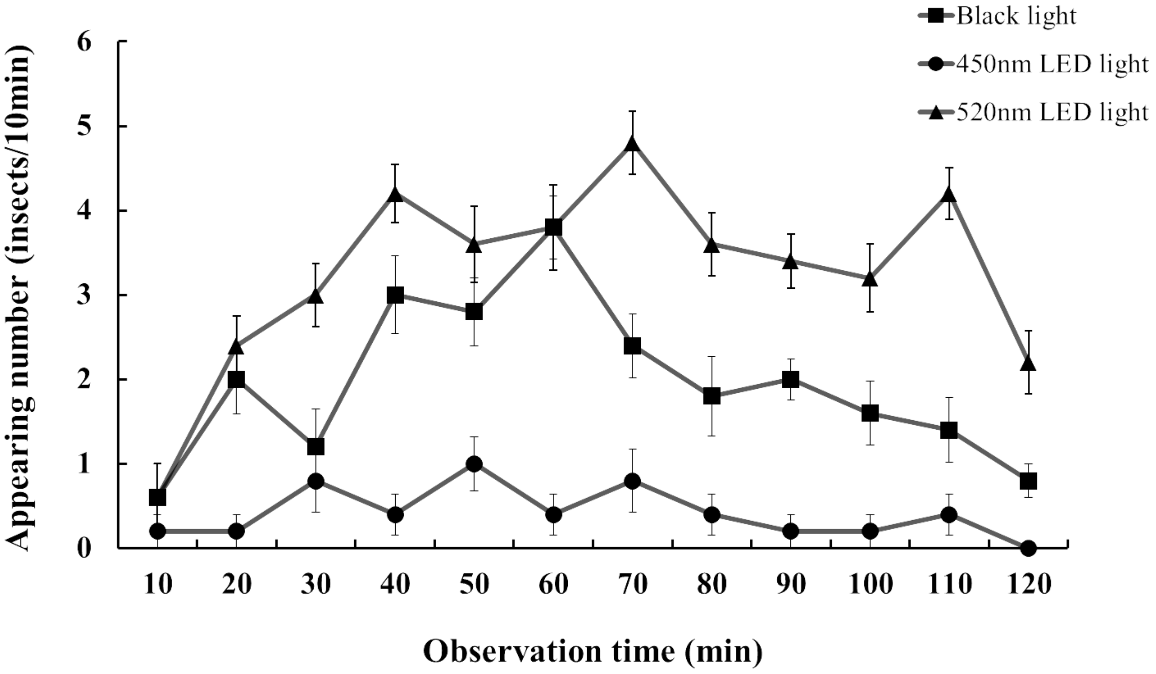

Figure 5. Phototactic response tendency of *M. separata* adults to different light sources as a time series in the net cage. The figure was derived from Figure 4. Each value indicates the number of adults that appeared for each observation time (10 minutes) in the videos of each experimental group. The error bar at each peak indicates the SEM.

Tables

Table 1. Wavelength and irradiance of LED lights

Light color	Wavelength (Mean ± S. E) (nm)	Irradiance under 200 lux (Mean ± S. E) (μW/cm^2)
Ultraviolet	365±3	89.3±3
Ultraviolet	385±1	107.6±4
Violet	400±2	41.7.8±3
Blue	450±3	39.4±2
Green	520±3	29.8±2
Yellow	590±3	57.8±3
Red	625±3	118.6±5
Dark Red	680±1	676.4±7
Infrared	740±4	2047.3±12
White	420~650	64.2±3

Table 2. The attraction rate of *M. separata* to LED lights of 10 wavelengths and black light under optimum conditions[1]

Wavelength (nm)	Luminance intensity (lux)	Exposure time (min)	Insect number (mean±SEM)		Ratio[2] (L:D)	Attraction rate[3] (%)	Relative attraction rate[4]
			Light side (Attraction)	Dark side (Repellent)			
365	50	40	13.67±0.89b	4.33±1.20b	3.15	45.56	0.97619
385	50	40	16.33±0.33b	4.67±0.33b	3.50	54.44	1.166667
400	50	40	16.67±0.33b	5.33±0.88b	3.13	55.56	1.190476
450	150	30	17.00±0.58b	4.00±0.58b	4.25	56.67	1.214286
520	200	40	19.33±0.33a	3.67±0.78b	5.27	64.44	1.380952
590	100	40	15.33±0.88b	9.67±0.33a	1.59	51.11	1.095238
625	150	10	15.00±0.58b	9.33±0.33a	1.61	50.00	1.071429
680	50	30	13.67±0.33b	4.00±0.57b	3.42	45.56	0.97619
White	50	40	15.33±1.45b	5.33±1.20b	2.88	51.11	1.095238
IR-740[5]	-	60	14.67±0.88b	5.67±1.20b	2.59	48.89	1.047619
BL (365)[6]	-	40	14.00±0.58b	7.00±0.58ab	2.00	46.67	1

[1] Each value is the average of three replicates under optimum conditions, using 30 insects per time.

[2] Each value indicates the ratio of insect numbers in the light side and the dark side.

[3] Attraction rate (%) is the average percentage of the 30 *M. separata* adults attracted to the light side under optimum conditions.

[4] Relative attraction rate indicates the ratio of the attraction rate of each group to the attraction rate of the black light (control).

[5] Each value is the average of three replicates showing the attraction rate to 5 W infrared (740 nm) LED light.

[6] Each value is the average of three replicates showing the attraction rate to 18 W the black light (control).

Different letters in column express significant differences according to the Tukey HSD test ($P<0.05$).