Evaluation of High Power Light Emitting Diodes (HPLEDs) as Potential Attractants for Adult *Spodoptera exigua* (Hübner) (Lepidoptera: Noctuidae)

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To evaluate high-power light-emitting diodes (HPLEDs) as potential attractants for *Spodoptera exigua* adults, attractiveness of specific wavelengths, illuminance intensity, and light-exposure times were investigated and compared to that of fluorescent light. The white light (40 lux treatment) attracted significantly more *S. exigua* than other attractants. The optimal light-exposure time, based on the highest attraction rate, was 60 min. Evaluation of attraction and repellent rates under optimal conditions showed the white HPLED had the highest attraction rate (91.1%), and the red HPLED had the highest repellence rate (33.3%). Based on relative efficiency values, the white HPLED was about 9.14 times as efficient as the fluorescent light. These data clearly showed that *S. exigua* showed the greatest attraction to the white HPLED at 40 lux intensity and 60 min light-exposure time.

Key words: high-power light-emitting diode, illuminance intensity, light-exposure time specific wavelength, *Spodoptera exigua*

During the last several decades, the advances of cultivation technology, along with a sharp increase in greenhouse cultivation, have enhanced the yields and qualities of various crops. However, the cultivation of crops in greenhouses is facing several problems, such as environmental pollution by toxic, chemical pesticides (health hazard to farmers as well as consumers), increasing pest resistances to pesticides, and the rising costs, due to repeated pesticide usage, of crop production [Ahn *et al*., 1998; Mutwiwa and Tantau, 2005; Kordali *et al*., 2008]. In particular, among the most widely known examples of pest resistances, *Spodoptera exigua* (Hübner) is a significant polyphagous pest in greenhouse and open fields [Jongsma *et al*., 1996; Smagghe *et al*., 2003; Kang *et al*., 2008]. In this regard, many researchers have sought assiduously for new insecticides and natural enemies that might control *S. exigua* [Park *et al*., 2000; Kim, 2001]. However, the intensive use of various methods for controlling this pest has caused it to develop pronounced resistance against chemical insecticides, insect growth regulators, and biological agents [Maclntosh *et al*., 1990; Kim *et al*., 2006]. A recent report revealed that customers are most concerned about food safety regarding their own health; thus, interest in eco-friendly, sustainable agriculture is increasing [Sengottayan *et al*., 2006]. Accordingly, researchers urgently need to develop safer and more efficient alternatives to the conventional methods for controlling *S. exigua*.

Recently, light-emitting diodes (LEDs) have emerged as one of the most important technologies for developing sustainable agricultural systems in the twenty-first century due to their numerous advantages as artificial light sources for controlled-environment plant growth applications. These advantages include stimulating plant growth, functional improvement, and eco-friendliness. They also have adjustable illuminance intensity and quality, and are small sized, with extended operational

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life, wavelength specificity, high energy efficiency, high shock resistance, and low thermal energy output [Tamulaitis *et al*., 2005; Wu *et al*., 2007]. Moreover, specific LED wavelengths were reported to be potential pest control agents due to their high attractive and repellent effects against hygienic and agricultural pests [Bishop *et al*., 2004; Burkett and Butler, 2005; Bentley *et al*., 2009; Jung *et al*., 2009]. However, both the high cost and low power of LEDs have led the current researches to focus on the improved luminance efficient LED devices [Tamultitis *et al*., 2005; Hogewoning *et al*., 2007; Wu *et al*., 2007], although, to date, relatively few studies have evaluated High-Power LEDs (HPLED) with respect to agricultural pest control. According to Kishan and Thoma [2008], three characteristics of light may influence insect behavior: specific wavelength, illuminance intensity, and light-exposure time. Thus, the responses of HPLEDs lighting source, illuminance intensities (20-100 lux), and light-exposure times (20-100 min) were examined to determine their attractive effect on *S. exigua* adults, using 5-color HPLEDs wavelengths (blue, green, red, white, yellow). Furthermore, in order to investigate its commercial potential, the illuminance efficiencies of the five HPLEDs wavelengths in 20-100 lux were compared with that of the commonly used fluorescent light.

Materials and Methods

Insects. The larvae of *S. exigua* were from the National Academy of Agricultural Science, RDA (Suwon, Korea). They were reared on an artificial diet including distilled water (75.7%), kidney bean powder (8.1%), wheat germ (8.1%), dried yeast (5.2%), and agar (1.5%) and maintained at 27±0.5°C and 60±5% RH, and a 16 L:8 D photoperiod cycle in insect breeding dishes (10 cm diameter×4 cm deep). The adults of *S. exigua* were incubated in a growth chamber (35×35×35 cm) under the same conditions. Subsequently, 30 adults were collected by a converted vacuum cleaner, and transferred into a 10×11 cm plastic container for the light response experiments.

Light source. The HPLEDs were purchased from the Ciel Light Corporation (Seoul, Korea) and the Photron Corporation (Ansung, Korea). The colors, part numbers, wavelengths, luminous flux (lm), and maximum power consumption (W) chosen for testing were as follows: blue (CL-1W-UBB, 470±10 nm, 15.0±3.1 lm, 1 W), green (CL-1W-UPGB, 520±5 nm, 45.0±3.5 lm, 1 W), yellow (PP592-8L61-AOBI, 590±5 nm, 40.0±10.0 lm, 1 W), red (CL-1W-URB, 625±10 nm, 35.0±1.2 lm, 1 W), and white (CL-1W-URB, 450-620 nm, 60.0±4.6 lm, 1 W). All HPLED products were mounted on aluminum metal-core printed circuit boards. The HPLED circuit boards (7 ×14 cm) consisted of 40 HPLEDs of one color. A large circuit board (30×15 cm) was designed to be wall-mounted or attached to the light side of the test chamber together with three HPLED circuit boards to allow quick and easy replacement (Figs. 1 and 2). The light intensity of large circuit board could be adjusted by the electric power controller and power supply (S-100-36: MEAN WELL Technology Co., Ltd, Suzhou, Taiwan). These HPLEDs were compared with the fluorescent light bulb (T5-508W, Hangzhou Lijing-Lighting Co., Ltd, Hangzhou, China), which served as a control.

Test chamber. The test chamber designed by Oh and Lee [2010] was used as follows. The test chamber comprised an opaque acrylic body (50×150×30 cm) and two transparent acrylic walls for light-exposure, which were fitted at both ends of the inside chamber (Figs. 1 and 2). Both ends of the outside chamber were removable covers including the air circulation system and light source (HPLED or fluorescent light). The power supply was a standard, 220-V alternating electricity source. The insect entrance holes were made at the center of chambers to efficiently disperse the *S. exigua* adults; nylon netting inside the chamber prevented the insects from escaping. The inside chamber consisted of two movable-plates and opaque partition walls for controlling the light-exposure and terminating the insect responses. The test chamber was maintained at 27±0.5°C and 60±5% RH throughout two holes (10×10 cm covered with wire netting) in the rear wall.

Bioassay. The responses of *S. exigua* adults to the HPLEDs light source were tested under three conditions, including specific wavelength, illuminance intensity, and light-exposure time in the test chamber. After 30 adults of *S. exigua* were collected by a converted vacuum cleaner, they were released into the test chamber through the insect entrance hole. The test chamber was maintained at 27±0.5°C and 60±5% relative humidity in darkness. All HPLED illuminances (lux) were measured from the middle position (70 cm) of the test chamber using an illumination meter (LM-332, AS ONE Co., Ltd, Tokyo, Japan). The attractiveness of the five HPLEDs to *S. exigua* adults were determined by counting the number of existing moths in the 'light' and 'dark' side of the test chamber. First, the attractiveness of the five HPLEDs illuminance intensity was determined by calculating the insect attraction rates, obtained by taking five measurements between 20 and 100 lux, inclusive, at 20-lux intervals. In the second experiment, the optimal illuminance intensity established above was used to examine the attraction rates of insects at 20 min intervals (20, 40, 60, 80, and 100 min), to determine the most effective light-exposure time. Finally, to determine which HPLEDs held the greatest

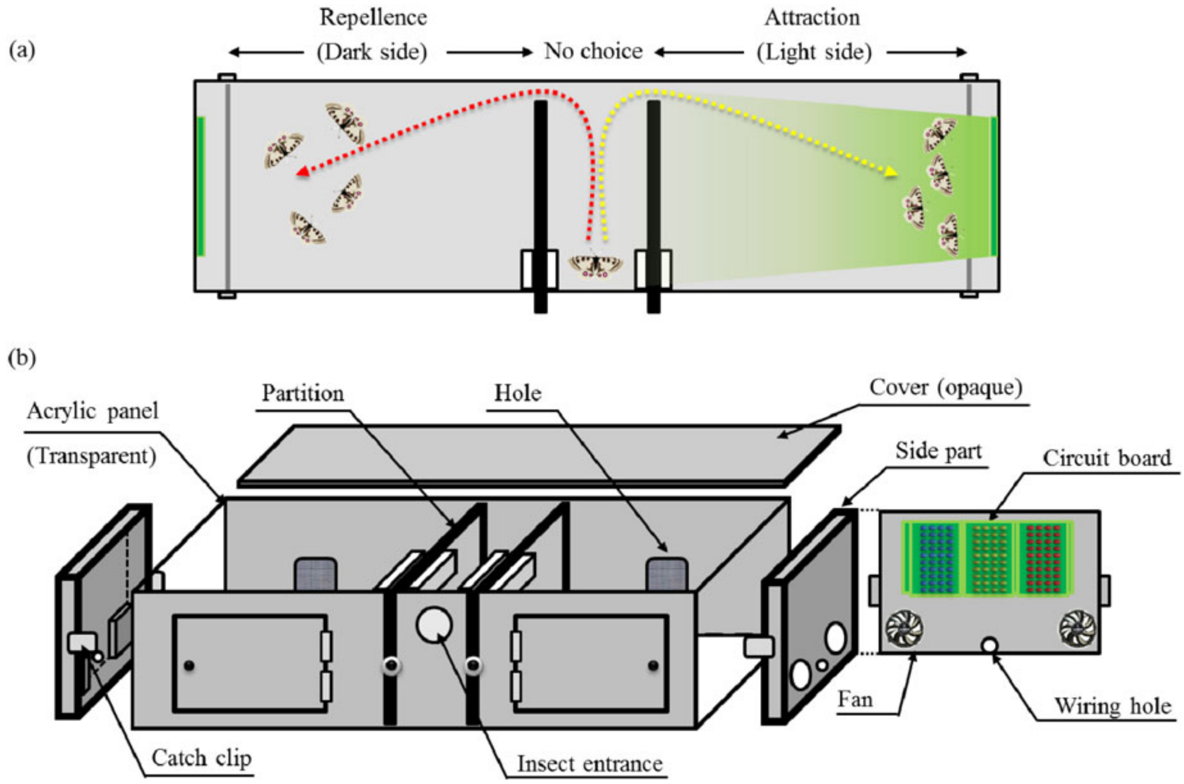

Fig. 1. Experimental layout for effective examination of HPLEDs in the laboratory. (a) Top view of the test chamber. (b) Side view of three-dimensional of the test chamber.

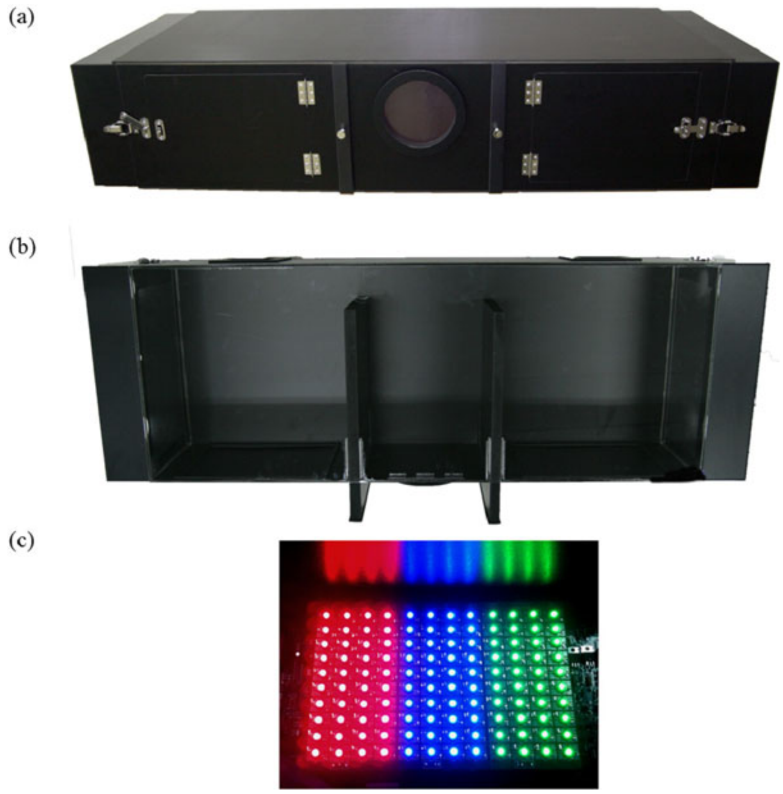

Fig. 2. Photograph of the test chamber used for the laboratory using by HPLEDs. (a) Facade view, (b) top view, and (c) HPLEDs circuit board of the test chamber.

attraction for *S. exigua*, each of the five HPLEDs was repeatedly measured under optimal conditions in terms of illuminance and light-exposure time. All experiments were repeated three times.

Statistical analysis. The one-way analyses of variance (ANOVA) were used to compare the numbers of *S. exigua* adults in the attraction tests, analyzing the data using SPSS statistical software (version 18.0, SPSS Inc., Chicago, IL). Duncan's multiple-range test was performed to compare differences among the mean values. Data were expressed as means±standard error of the mean (SEM).

Results

To evaluate HPLEDs as potential attractants of the *S. exigua* adult, the attractiveness of specific wavelengths, illuminance intensities, and light-exposure times were examined by comparison to each other and to fluorescent light, which served as a light control. Attraction responses varied according to the tested HPLED, the illuminance intensity, and the light-exposure time (Tables 1-4).

In the first trial, the *S. exigua* attraction rates were examined at varying illuminance intensities (20-100 lux) among the five HPLEDs and the fluorescent light. For all light treatments, 40 lux attracted a significantly higher number of *S. exigua* adults; the attraction rate dropped dramatically as illuminance intensity increased (Table 1). In particular, among the HPLEDs, the white HPLED, having a multiple wavelength (450-620 nm), showed the highest attraction rate (87%) at 40 lux, followed by the green HPLED (82%), the fluorescent bulb (78%), the blue HPLED (73%), the yellow HPLED (63%), and the red HPLED (53%).

In the second trial, the *S. exigua* attraction rates for varying durations of light-exposure (20-100 min) among the five HPLEDs and the fluorescent light were examined. The optimal light-exposure time for all light treatments was 60 min, with no significant differences in the percentages of attracted *S. exigua* adults as light-exposure duration increased above 60 min (Table 2). In addition, the white HPLED showed the highest attraction rate (90%) at the optimal light-exposure time, followed by the green HPLED (87%), the fluorescent light (80%), the blue HPLED (80%), the yellow HPLED (63%), and the red HPLED (55%).

In the third trial, the *S. exigua* attraction and repellent rates were examined among the five HPLEDs and the

Table 1. *S. exigua* attraction rates across varying illuminance intensities (lux) of the five HPLEDs and the fluorescent control[1)]

Color	Wavelength (nm)	Attraction rate (%)[2)]				
		20 lux	40 lux	60 lux	80 lux	100 lux
Blue	470±10 nm	63	73	70	63	50
Green	520±5 nm	75	82	77	72	65
Yellow	590±5 nm	57	63	53	33	30
Red	625±10 nm	43	53	47	33	23
White	450-620 nm	73	87	83	76	68
Fluorescent	380-800 nm	73	78	75	70	63

1)Each value is the average of 3 determinations after 30 min exposure, with 30 adult insects per replication.
2)Attraction rate (%) is the average percentage of the 30 *S. exigua* adults that were attracted to various illuminance intensities.

Table 2. *S. exigua* attraction rates across varying light-exposure times (min) among the five HPLEDs and the fluorescent control[1)]

Color	Wavelength (nm)	Attraction rate (%)[2)]				
		20 min	40 min	60 min	80 min	100 min
Blue	470±10 nm	60	74	80	81	81
Green	520±5 nm	64	83	88	88	89
Yellow	590±5 nm	33	63	63	64	64
Red	625±10 nm	37	54	55	56	56
White	450-620 nm	71	87	90	90	91
Fluorescent	380-800 nm	63	79	80	81	81

1)Each value is the average of 3 determinations per each light-exposure time, at 40 lux, using 30 adult insects per replication.
2)Attraction rate (%) is the average percentage of the 30 *S. exigua* adults attracted by the end of each light-exposure time.

Table 3. *S. exigua* attraction and repellent rates of the five HPLEDs and the fluorescent light under selected, optimal conditions[1)]

Color	Wavelength (nm)	Insect population (mean±SE)			Attraction rate (%)[2)]	Repellent rate (%)[3)]
		Light side	No choice	Dark side		
Blue	470±10	24.3±0.3[ab]	2.0±0.6	3.7±0.9	81.1	12.2
Green	520±5	26.7±0.9[ab]	2.0±0.6	1.6±0.9	88.9	5.6
Yellow	590±5	19.0±1.7[c]	1.7±0.3	9.3±1.5	63.3	31.1
Red	625±10	17.0±1.0[c]	2.3±0.3	10.0±1.0	56.7	33.3
White	450-620	27.3±0.9[b]	1.7±0.7	1.0±0.6	91.1	3.3
Fluorescent	380-800	24.0±0.6[a]	2.3±0.6	3.7±0.3	80.0	12.2

[1)]Each value is the average of 3 determinations using the optimal light-exposure time at 40 lux, with 30 adult insects per replication.
[2)]Attraction rate (%) is the average percentage of the 30 *S. exigua* adults attracted toward the light side.
[3)]Repellent rate (%) is the average percentage of the 30 *S. exigua* adults that were repelled toward the dark side.
[a-c]Different letters within the same column are significantly different (Duncan's test, $p<0.05$).

Table 4. Illuminance efficiencies of the five HPLEDs and the fluorescent light in the test chamber

Color	Wavelength (nm)	Illuminance efficiency (lux/W)[1)]					RE[2)]
		20 lux	40 lux	60 lux	80 lux	100 lux	
Blue	470±10 nm	43.48	52.78	51.42	51.05	50.63	8.71
Green	520±5 nm	27.40	28.97	28.71	28.37	27.93	4.78
Red	625±10 nm	55.56	62.70	61.08	60.85	60.61	10.34
Yellow	590±5 nm	18.52	19.42	19.05	18.56	17.67	3.20
White	450-620 nm	43.48	55.42	53.59	52.63	51.02	9.14
Fluorescent	380-800 nm	5.56	6.06	5.94	5.88	5.73	1.00

[1)]Illuminance efficiency (lux/W)=illuminance per watt of HPLED.
[2)]Relative efficiency (based on the 40 lux results)=illuminance efficiency value of HPLED/illuminance efficiency value of fluorescent.

fluorescent light under selected, optimal conditions; the white HPLED exhibited the highest attraction rate (91.1%) ($p<0.05$) (Table 3). In contrast, the red (33.3%) and yellow (31.1%) HPLEDs showed the most effective repellence compared with the other light treatments, and the white (3.3%) and green (5.6%) HPLEDs had the lowest *S. exigua* repellant rates.

Evaluation of the illuminance efficiencies among the five HPLEDs and the fluorescent light in the test chamber revealed the 40-lux intensity of the various illuminance intensities (20-100 lux) exhibited optimal efficiency. These intensity results were similar to the results in the test for optimal illuminance intensity for attracting *S. exigua* adults (Table 4). Moreover, the relative efficiency (RE) value of the red HPLED was about 10.34 times as efficient as the fluorescent light (light control), followed by the white HPLED (9.14 times), the blue HPLED (8.71 times), the green HPLED (4.78 times), and the yellow HPLED (3.20 times).

Discussion

In spite of the synthetic insecticides with various health and environmental problems, they are still used extensively, due to the absence of effective replacement agents. Hence, many studies have focused on the development of eco-friendly pest control technologies for sustainable agricultural systems. LEDs could be useful tools due to their pronounced attractive/repellent effects against many pests [Hoel *et al*., 2007]. This phenomenon occurs because most insect eyes have multiple photoreceptors accepting specific wavelengths; insects, therefore, possess color vision, to sense approaching dangers [Birscoe and Chitka, 2001]. Several previous studies have reported that color and intensity of lights are the most important factors in attracting insects, but, as yet, the use of LEDs for pest control is still in the early stage [Hoel *et al*., 2007]. For example, some researchers have only tested LEDs as substitutes for incandescent light bulbs in mosquito light traps [Hoel *et al*., 2007]. Therefore, evaluation of the usefulness of HPLEDs against *S. exigua* adults is presently difficult, despite the fact that this species causes serious damage to agricultural crops. The present study aimed to evaluate the attraction of *S. exigua* adults to specific wavelengths, illuminance intensities, and light-exposure times by examining five HPLEDs and comparing them to the commonly used fluorescent light to investigate their illuminance efficiencies.

In these experiments, the light response of the *S. exigua* adults showed a significant attraction toward the light side of the test chamber. Our results indicated that the attraction rate depended on the specific wavelength and the illuminance intensity. In particular, the *S. exigua* adults showed a significantly more favorable response to the white HPLED than to other light source. Among the wavelengths, the green HPLED also possessed a highly significant attraction for the pests. Hoel *et al.* [2007] showed that *Phlebotomus papatasi* (sand fly) and mosquito species were attracted more strongly to red light than to green or white light. However, previous study showed that *Culicoides brevitarsis* Kieffer exhibited the highest attraction to green and white LEDs, in comparison with red and yellow LEDs; furthermore, a green LED trap appeared the most effective at capturing *Euscepes postfasciatus* (Fairmaire) and *Bemisia tabaci* (Gennadius) in a potato field or greenhouse [Chu *et al*., 2003]. Possible reasons for the variable responses of insects to LED lights could be due to the difference in species and in experimental conditions, such as different design and light devices, light intensity, and so forth [Kishan and Thoma, 2008].

As shown in Table 1, when the illuminance intensity was increased from 20 to 40 lux, the attraction rate also increased, in all treatment groups, until 40 lux was reached, after which the attraction rate began dropping dramatically as illuminance increased. It is widely known that light intensity plays a significant role with higher intensity more attractive than lower intensity [Mutwiwa and Tantau, 2005; Hoel *et al*., 2007]. However, our results showed that lights attraction/repellent effects on the *S. exigua* adults changed as we selectively varied the light intensity. These results are similar to findings regarding other insects [Kishan and Thoma, 2008].

Table 2 shows how, with all treatment groups, the attraction rate gradually increased as the insects light-exposure time increased, up to 60 minutes duration, at which point the rates plateaued as light-exposure time continued to increase from 60 to 100 min. These results indicated that the attraction rate was very strongly affected by, not only specific wavelength and illuminance intensity, but also light-exposure time. Therefore, in our experiments examining different wavelengths using optimal conditions, the attraction rate in all treatment groups slightly increased. The white HPLED had the highest attraction rate for the *S. exigua* adults, and the red HPLED had the highest repellent rate (Table 3). Furthermore, in order to clarify the illuminance efficiency of the tested HPLEDs, the REs of the five HPLEDs were compared to fluorescent light, based on the results at the 40 lux; white HPLED was about nine times more efficient than fluorescent light (Table 4).

Results of the present study clearly show that the white HPLED was the most attractive to the *S. exigua* adults, and 40 lux intensity was the most suitable for pest control. These results demonstrate that white HPLEDs has the potencial to protect greenhouse crops from invasion by the *S. exigua* adults, which is the world's most economically-significant polyphagous insect species. Accordingly, further research is needed to compare efficiencies of HPLEDs to examine their effects on a wide range of greenhouse pests. To enhance the attraction rate of the *S. exigua* adults, the combined effects of multiplex HPLEDs on the *S. exigua* adults should be evaluated for further development of sustainable agricultural systems using the special function of HPLEDs.

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