Phototactic behavioral response of agricultural insects and stored-product insects to light-emitting diodes (LEDs)

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Abstract Agricultural insects and stored-product insects are influenced by luminance intensities, exposure times, and wavelengths of light-emitting diodes (LEDs). Based on the phototactic behaviors of the agricultural insects, green or blue LEDs are most attractive for Bemisia tabaci, Trialeurodes vaporariorum, Myzus persicae, Liriomyza trifolii, Spodoptera exigua, and Spodoptera litura. Green LED attracts Plutella xylostella and Frankliniella occidentalis. Similarly, green or blue LEDs are more attractive to agricultural insects, such as Liriomyza sativae, Sogatella furcifera, and Nilaparvata lugens, than other wavelength LEDs. Concerning the phototactic behaviors of the stored-product insects, red LED is attractive for, in descending order Tribolium castaneum, Sitophilus zeamais, Lasioderma serricorne, and Tyrophagus putrescentiae. Blue LED captures most Sitophilus oryzae and Sitotroga cerealella. Red and blue LEDs are more attractive for stored-product insect pests rate than ultraviolet LED and green, yellow, white, and infrared LEDs. Based on the attraction rate of the stored-product insects on granary, red LED is most attractive for S. cerealella and Plodia interpunctella. These light sources are effective in controlling agricultural and stored-product insects. Applying LED technology for greenhouses and granaries along with conventional traps reduces crop loss due to moths, beetles, aphids, and weevils. LEDs have potential value in integrated pest management.

Keywords Agricultural insect · Behavior response · Light-emitting diodes · Light perception · Phototaxis · Stored-product insects

Introduction

Many countries are using synthetic insecticides as the primary means of controlling insect pests [1, 2]. However, repeated use of synthetic insecticides can increase the development of resistance in the insect pests and has negative effects on the environment and nontarget insects [2, 3]. Efforts are ongoing to develop sustainable alternative and eco-friendly methods, such as the use of electric traps, food traps, and natural insecticides [1–4].

Phototaxis is the behavior of insect species in response to light sources. This movement is influenced by the light wavelength, and the quality and intensity of the light source [5]. In general, insect pests can perceive light ranging in wavelength from 350 to 700 nm and respond in diverse ways [6]. The alternative techniques being developed include phototaxis; electric traps equipped with black and incandescent light bulbs are used for surveillance, for example. The incandescent bulb as the standard light commonly used in light traps ranges in wavelength from 350 to 700 nm with a maximum output wavelength at 700 nm [7]. Insect species can be attracted or repelled to special light sources, such as artificial lights [8]. Certain insect species exhibit a directional response to light-emitting sources including high- or low-intensity light [9]. The use of artificial light sources in integrated pest management (IPM) has increased globally [10]. Light-emitting diodes (LEDs) have emerged as an important technology in the development of agricultural systems [11, 12]. The many advantages of LEDs include the eco-friendly technology, functional improvement, plant...
LED traps may be a potential alternative to commercial traps for mass trapping and phototactic monitoring of insect pests. Specific wavelength LED sources are being used for monitoring as well as trapping [7, 15]. Pest insects will move toward light lamps or other illuminations in outdoor settings [16]. This phototactic behavior of pest insects is the basis of the design of electronic insect traps [16]. The light traps are equipped with LED sources; they effectively attract agricultural and stored grain insect pests including aphids, beetles, moths, and weevils and prevent the entry of these insects into greenhouses and granaries [17, 18]. Interest is growing in control technology that exploits insect behaviors to light sources as an alternative to synthetic insecticides [16, 19]. Here, we review the advanced control technologies of insect species that employ new light sources including LEDs.

**Classification of phototactic behavioral responses to light sources of various insects**

Insect behavior to light is varied and can be categorized [20]. The typical behavior is phototaxis. Insects display several phototactic responses including attraction (movement toward the light source: positive phototaxis) and repulsion (movement away from the light source: negative phototaxis). Optimal conditions, which include effective
wavelengths, exposure time, and intensities to light source, are diverse among insect species [21, 22]. Negative phototaxis could be useful to prevent entrance of pest insects to greenhouses and granaries [23, 24]. Behavioral responses to light by insect species also include light adaptation, circadian periodicity, photoperiodism, and light toxicity [20]. Nocturnal insects can adapt to light sources; typical adaptive behaviors are diminished migration, settling near the light source, and mating [20]. Circadian periodicity is daily behavioral response that encompasses courtship, feeding, flight, and locomotion [25]. Artificial light at night can change the diurnal or nocturnal responses and timing of insect species [26], which represents a phase shift in chronobiology [27]. Photoperiodism is the physiological behavior of insect species to light, such as day light. The start of resting can be prevented by repeatedly exposing insects to light sources for some days [28]. Insects that do not enter diapause cannot overwinter. Continuous light irradiation is structurally damaging and causes light toxicity [29]. Photo-irradiation is also useful for treatment of crops before the post-harvest in the greenhouse and granary settings. Insect behaviors to light sources are significantly influenced by various factors of the light, such as intensity, single or combined wavelengths, exposure time, and

| Table 1 Phototactic behavior of agricultural insects to LED sources |
|------------------|------------------|------------------|------------------|------------------|------------------|
| Pests                  | Wavelength (color) | Luminous intensity (lx) | Time (min) | Number of adults (mean ± SEM) | Attraction rate (%)a | References |
|------------------------|--------------------|--------------------------|-------------|-------------------------------|----------------------|------------|
| Bemisia tabaci         | 520 ± 5 nm (green) | 40                       | 90          | 25.6 ± 0.3 4.4 ± 0.3          | 85.3                 | [34]       |
|                        | 470 ± 10 nm (blue) | 40                       | 90          | 26.7 ± 1.5 3.3 ± 0.9          | 89.0                 |            |
|                        | BLB (control)      | –                        | 90          | 26.9 ± 0.6 3.1 ± 0.3          | 89.6                 |            |
| Trialeurodes vaporariorum | 520 ± 5 nm (green) | 40                       | 90          | 28.9 ± 0.7 1.1 ± 0.8          | 96.6                 | [36]       |
|                        | 470 ± 10 nm (blue) | 40                       | 90          | 29.2 ± 1.3 0.8 ± 0.5          | 97.4                 |            |
| Myzus persicae        | 520 ± 5 nm (green) | 40                       | 120         | 25.6 ± 0.9 4.4 ± 1.2          | 85.3                 | [37]       |
|                        | 470 ± 10 nm (blue) | 60                       | 120         | 22.5 ± 1.5 7.5 ± 2.9          | 75.0                 |            |
|                        | BLB (control)      | –                        | 120         | 18.5 ± 1.5 11.5 ± 2.2         | 61.7                 |            |
| Liriomyza trifolii     | 520 ± 5 nm (green) | 60                       | 120         | 29.9 ± 0.3 0.1 ± 0.1          | 99.7                 | [17]       |
|                        | 470 ± 10 nm (blue) | 80                       | 120         | 27.3 ± 2.0 2.7 ± 2.0          | 91.2                 |            |
|                        | BLB (control)      | –                        | 120         | 21.3 ± 1.7 8.7 ± 2.1          | 71.1                 |            |
| Spodoptera exigua      | 520 ± 5 nm (green) | 40                       | 100         | 27.1 ± 0.9 2.0 ± 0.6          | 90.3                 | [11]       |
|                        | 470 ± 10 nm (blue) | 40                       | 100         | 24.3 ± 0.3 2.0 ± 0.6          | 81.1                 |            |
|                        | BLB (control)      | –                        | 100         | 24.0 ± 0.6 2.3 ± 0.6          | 80.0                 |            |
| Spodoptera litura      | 520 ± 5 nm (green) | 40                       | 60          | 19.3 ± 0.7 6.3 ± 0.3          | 64.3                 | [33]       |
|                        | 470 ± 10 nm (blue) | 40                       | 60          | 17.3 ± 0.8 7.0 ± 0.6          | 57.7                 |            |
|                        | BLB (control)      | –                        | 60          | 15.0 ± 1.2 7.3 ± 1.5          | 50.0                 |            |
| Plutella xylostella    | 520 ± 5 nm (green) | 60                       | 15          | 29.5 ± 0.2 0.5 ± 0.3          | 98.3                 | [32]       |
|                        | BLB (control)      | –                        | 15          | 26.0 ± 0.6 0.0 ± 0.0          | 86.7                 |            |
| Frankliniella occidentalis | 520 ± 5 nm (green) | 40                       | 90          | 13.3 ± 0.8 15.1 ± 0.9         | 44.3                 | [38]       |
|                        | BLB (control)      | –                        | 90          | 11.7 ± 1.1 18.3 ± 0.7         | 39.0                 |            |

a Attraction rate (%) is the average percentage of pests attracted under optimal conditions
differences of light intensity and color to those of ambient lighting [19, 30]. In the remainder of this minireview, we discuss the technologies being currently being used to control many insect species.

**Phototactic behavior to LED source for agricultural insect pests**

Agricultural insect species include aphids, leaf miners, moths, and whiteflies. Their reactions are influenced by various characteristics of light, such as luminance intensity, light exposure time, and light wavelength [31]. Evaluation of the phototactic responses of insect species to these aforementioned aspects typically uses a chamber capable of dark and illuminated settings (Figs. 1, 2). Phototactic behavior of agricultural insect species has been amply correlated with characteristics of light [11, 32–38]. *Bemisia tabaci* and *Trialeurodes vaporariorum* showed a significantly more favorable response to the green (520 nm) and blue (470 nm) LEDs at a luminance intensity of 40 lx and exposure time of 90 min than to red (625 nm) and yellow (590 nm) LEDs [34, 36]. Under optimal light exposure times and luminance intensities, LED light sources that emit relatively short wavelengths attract agricultural insect species [11, 32–38] (Table 1). Based on the phototactic

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Fig. 3 Model of cross section (A), three dimension (B), and insert tube (C) in modified Y-maze [47]
behaviors, green and/or blue LEDs show the highest attraction rate against *Bemisia tabaci* (85.3 and 89.0%), *Trialeurodes vaporariorum* (96.6 and 97.4%), *Myzus persicae* (85.3 and 75.0%), *Liriomyza trifolii* (99.7 and 91.2%), *Spodoptera exigua* (90.3 and 81.1%), *Spodoptera litura* (64.3 and 57.7%), *Plutella xylostella* (green LED, 98.3%), and *Frankliniella occidentalis* (green LED, 44.3%) [11, 32–38]. In contrast, the relatively long wavelengths of red light (625 nm) and infrared light (IR, 730 nm) are repellent for the leaf miner (*L. trifolii*), moths (*S. litura* and *P. xylostella*), and whitefly (*T. vaporariorum*) [32, 33, 35, 36]. Green and/or blue LEDs are attractive for several agricultural insect pests including *T. vaporariorum*, *Liriomyza sativae*, *Sogatella furcifera*, and *Nilaparvata lugens* [39, 40]. Matteson and Terry [41] reported that *F. occidentalis* exhibited strong attractiveness to the blue LED traps. Vaishampayan et al. [42] evaluated the ultraviolet (UV, <400 nm), yellow-green region (520–610 nm), and red (610 to ca. 700 nm) light in attracting *T. vaporariorum* and found that the yellow-green region attracted

### Table 2  Phototactic behavior of stored-product insects to LED sources

| Pests                    | Wavelength (color) | Luminous intensity (lx) | Time (h) | Number of adults (mean ± SEM) | Attraction rate (%)<sup>a</sup> | References |
|--------------------------|--------------------|-------------------------|----------|-------------------------------|---------------------------------|------------|
| *Lasioderma serricorne*  | 625 ± 10 nm (red) | 100                     | 1.5      | 9.3 ± 3.4                     | 11.9 ± 4.0                      | 8.8 ± 0.9  | 31.0 | [24] |
|                         | BLB (control) –    | –                       | 1.5      | 8.7 ± 1.3                     | 7.6 ± 2.2                       | 13.7 ± 0.9 | 29.0 |
| *Sitophilus oryzae*     | 470 ± 10 nm (blue) | 25                      | 48       | 25.3 ± 0.7                    | 2.8 ± 0.5                       | 1.9 ± 0.4  | 84.3 | [44] |
|                         | BLB (control) –    | –                       | 48       | 17.0 ± 0.9                    | 7.2 ± 0.6                       | 5.8 ± 0.4  | 56.7 |
| *Sitophilus zeamais*    | 625 ± 10 nm (red) | 25                      | 48       | 18.0 ± 1.0                    | 7.3 ± 1.3                       | 4.7 ± 1.3  | 59.8 | [45] |
|                         | BLB (control) –    | –                       | 48       | 8.2 ± 2.0                     | 12.3 ± 2.8                      | 9.5 ± 0.9  | 27.3 |
| *Sitotroga cerealella*  | 470 ± 10 nm (blue) | 60                      | 0.6      | 18.3 ± 0.6                    | 8.1 ± 1.5                       | 3.6 ± 0.6  | 61.0 | [17] |
|                         | BLB (control) –    | –                       | 0.6      | 17.4 ± 2.1                    | 2.2 ± 1.7                       | 10.4 ± 0.6 | 58.0 |
| *Plodia interpunctella* | 520 ± 5 nm (green) | 60                      | 0.5      | 22.0 ± 0.5                    | 2.1 ± 1.1                       | 5.86 ± 1.4 | 52.2 | [12] |
|                         | BLB (control) –    | –                       | 0.5      | 8.7 ± 2.1                     | 6.0 ± 1.5                       | 15.32 ± 1.8 | 28.9 |
| *Tribolium castaneum*   | 625 ± 10 nm (red) | 30                      | 48       | 29.4 ± 1.6                    | 0.6 ± 0.5                       | 0.0 ± 0.1  | 97.8 | [49] |
|                         | BLB (control) –    | –                       | 48       | 8.4 ± 1.5                     | 0.2 ± 0.1                       | 21.8 ± 2.6 | 28.0 |
| *Tyrophagus putrescentiae* | 625 ± 10 nm (red) | 40                      | 2        | 5.4 ± 2.7                     | 41.7 ± 1.7                      | 2.9 ± 1.6  | 18.0 | [47] |
|                         | BLB (control) –    | –                       | 2        | 2.2 ± 1.3                     | 44.5 ± 1.7                      | 3.3 ± 2.0  | 7.3  |

<sup>a</sup> Attraction rate (%) is the average percentage of pests attracted under optimal conditions.

### Table 3  Phototactic behavior of stored-product insects to LED sources in granary settings<sup>a</sup>

| Pests                    | Wavelength (color) | Luminous intensity (lx) | Time (days) | Number of adults (mean ± SEM) | Attraction rate (%)<sup>a</sup> | References |
|--------------------------|--------------------|-------------------------|-------------|-------------------------------|---------------------------------|------------|
| *Plodia interpunctella*  | 520 ± 5 nm (green) | 60                      | 4           | 199.1 ± 2.5                   | 66.3                            | [48]       |
|                         | BLB (control) –    | –                       | 4           | 94.1 ± 1.6                    | 31.4                            |            |
| *Sitotroga cerealella*  | 470 ± 10 nm (blue) | 60                      | 4           | 248.4 ± 1.9                   | 82.7                            | [48]       |
|                         | BLB (control) –    | –                       | 4           | 105.5 ± 2.1                   | 35.2                            |            |
| *Sitophilus zeamais*    | 625 ± 10 nm (red) | 60                      | 4           | 201.4 ± 2.9                   | 67.1                            | [49]       |
|                         | BLB (control) –    | –                       | 4           | 92.4 ± 2.0                    | 30.8                            |            |
| *Tribolium castaneum*   | 625 ± 10 nm (red) | 60                      | 4           | 244.5 ± 2.6                   | 81.5                            | [49]       |
|                         | BLB (control) –    | –                       | 4           | 90.4 ± 0.8                    | 30.1                            |            |

<sup>a</sup> Attraction rate (%) is the average percentage of pests attracted under optimal conditions.
the most individuals compared with ultraviolet and red light. The collective data indicate that light traps with green and blue LEDs have the potential to control the agricultural insects in IPM.

Phototactic behavior on stored-product insects to LED sources

Similar to the behaviors of agricultural insect species, the behavior of various stored-product insect pests, such as weevil and moth, are influenced by light sources [12, 15, 17, 43–46] (Fig. 3). Under optimal light exposure times and luminance intensities of each wavelength, red, green, and blue LEDs have proven to be most attractive for stored-product insect species [12, 17, 44–46]. Based on the phototactic behavior under laboratory conditions, red LED (625 nm) is more efficient in attracting *Sitophilus zeamais* (59.8%) and *Tribolium castaneum* (97.8%), but less efficient in attracting *Lasioderma serricorne* (31.0%) and *Tyrrophagus putrescentiae* (18.0%) [24, 47] (Table 2). Blue LED is significantly more effective in attracting *S. oryzae* and *Sitotroga cerealella* than UV (365 nm), green (510–520 nm), red (625–660 nm), and IR (730 nm) LEDs [17, 44]. Green LED best attracted *Plodia interpunctella* (52.2%) [12]. Based on the attraction rate under optimal conditions (luminous intensity of 60 lx and exposure time of 4 days), red LED showed the highest attraction rate against *S. cerealella* (67.1%) and *P. interpunctella* (81.5%) [48, 49] in a granary setting (Table 3). In the same setting, *P. interpunctella* (66.3%) and *S. cerealella* (82.7%) exhibited strong attractiveness to the green and blue LEDs, respectively [48] (Fig. 4). The effectiveness of LEDs has also been chronicled for blossom weevil (*Anthonomus pomorum*) and sweet potato weevil (*Euscepes postfasciatus*) [15, 50]. Nakamoto and Kubo [15] reported that light trapping of *E. postfasciatus* was more efficient using green (536 nm) LED. Hausmann et al. [50] found that the green and blue LEDs were more efficient in attracting and trapping *A. pomorum* than UV light. These optimal conditions of LED sources are an advantage to control insect pest behaviors. In future, the development of LED devices containing practical application is expected.

Study on physical control of insect pests by using light sources

The influence of LEDs on insect color and light perception with different wavelengths and on behavior, and the development of control technology involving new light sources has been described [19]. Physiological systems have been comprehensively utilized to measure the influence on many insect species in a wide range of wavelengths [51]. Phototactic responses of many insect species to LED sources have been investigated to clarify the relationship between insect behaviors and light wavelengths, with the goal of determining the effective attractant and repellent wavelengths for target insect pests [51]. The development of LED sources that are able to be used instead of incandescent light traps is an ongoing research interest. In addition, wavelengths of light that effectively attract parasitoids, which are natural enemies of insect pests, are being investigated [19].

In conclusion, LED equipment with various wavelengths can now be manufactured due to current technological advances, and new agricultural technology using light is starting to attract attention. Advances are also expected in the use of light for insect control as the results of these technological developments in lighting. Based on the new research being conducted by National Agricultural Research Organisation, we hope to ensure the further development of agricultural technology founded on a good balance of input from basic study in universities and independent administrative institutions and applied technology from private companies and public research institutes to establish the next generation of pest control technology.

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