Implications of open circuit voltage of light-emitting diodes installed for plant cultivation

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Abstract

This study investigated a light sensor function of light-emitting diodes (LEDs), the use of which is expanding in plant cultivations. Unimodal spectral LEDs of four types with respective emission peak wavelengths of 464, 501, 634, and 849 nm, and a white LED with a bimodal spectrum with 455-nm primary and 574-nm secondary peaks were used for this study. Open circuit voltage (V_{OC}) of up to 1–2 V was induced in the LEDs when they were irradiated with sunlight. The V_{OC} value of the 634 nm LED saturated with a low photon flux density can be used for binary discrimination between daylight and night. Each LED had a V_{OC} inducible threshold wavelength of incident light. By virtue of the wavelength threshold feature, existence of a plant leaf between a light source and the LEDs is detectable by comparing the V_{OC} values of blue-green range LEDs (464 nm, 501 nm) and near-infrared (NIR) LEDs (849 nm). Under leaf shadow, the NIR LED V_{OC} exceeded those of the blue-green range LEDs. Under natural incident sunlight, the V_{OC} s of the blue-green range LEDs were greater than that of the NIR LED. Another function of LEDs in agricultural use has been demonstrated.

Key words: Greenhouse, Photodiode, Photovoltaic effect, Plant factory, Vertical farming

1. Introduction

Plant cultivation studies conducted in experimental chambers using light-emitting diodes (LEDs) as the sole lighting source have been continued (Bula *et al.*, 1991; Massa *et al.*, 2008) since lettuce cultivation using red LEDs was planned for feeding astronauts fresh vegetables in a spacecraft (Kliss and MacElroy, 1990). The realization of blue LEDs (Akasaki *et al.*, 1993; Nakamura *et al.*, 1993), which enable emissions at the shorter wavelength peak of bimodal absorption spectra of chlorophylls, supported the role of LEDs as a light source for plant cultivation (Hernández and Kubota, 2016; Matsuda *et al.*, 2004). Subsequent declines of LED prices have led to commercial crop cultivation in closed, environmentally controlled facilities known as vertical farms (Benke and Tomkins, 2017; O'Sullivan *et al.*, 2019) and plant factories with artificial lighting (Kozai, 2013; Kozai *et al.*, 2020), which use numerous LEDs as light sources to drive photosynthesis, resulting in overwhelmingly high planting density, high growth rates, and high crop quality (Orsini *et al.*, 2020). Field and greenhouse cultivations also use LEDs for purposes such as supplemental lighting for photosynthesis support (Deram *et al.*, 2014; Hikosaka *et al.*, 2013), photomorphogenesis modification (Cope and Bugbee, 2013; Jeong *et al.*, 2014), metabolite synthesis activation (Kitazaki *et al.*, 2018; Kopsell *et al.*, 2014; Piovene *et al.*, 2015), and pest management (Cochard *et al.*, 2019; Stukenberg *et al.*, 2015). In addition to visible light

of the 400–700 nm wavelength range required for maintenance of the basic physiology of plants, far-red (Shibuya *et al.*, 2019; Zhang and Runkle, 2019) for photomorphogenesis and ultraviolet light (Huché-Thélier *et al.*, 2016) for metabolite synthesis are wavelength bands that improve crop quality.

In contrast to the original role of light emission, a photovoltaic effect is induced in an LED when light is illuminated onto the semiconductor die which usually converts the changes in electron energy levels into light (Filippo *et al.*, 2017; RayChaudhuri and Sen, 2009; Vannacci *et al.*, 2018; Vannacci *et al.*, 2019). Taking advantage of the photovoltaic feature, atmospheric turbidity and precipitable water measurements (Mims, 1992), atmospheric optical depth measurements (Acharya *et al.*, 1995), solar photometry and surface reflectance measurements (RayChaudhuri and Sen, 2009), power delivery and data transmission in a wireless and battery-less microsystem (Haydaroglu and Mutlu, 2015), distance and image sensors (Vannacci *et al.*, 2019), and a vegetation monitoring sensor (Kim *et al.*, 2019; Ryu *et al.*, 2010) have been realized using LEDs. The reported benefits of using LEDs as light sensors over photodiodes are affordability (Acharya *et al.*, 1995; Mims, 1992; RayChaudhuri and Sen, 2009; Ryu *et al.*, 2010), small size (Acharya *et al.*, 1995; Mims, 1992; RayChaudhuri and Sen, 2009; Ryu *et al.*, 2010), sturdiness (Acharya *et al.*, 1995; Mims, 1992; RayChaudhuri and Sen, 2009), wavelength band selectivity (Filippo *et al.*, 2017; RayChaudhuri and Sen, 2009; Ryu *et al.*, 2010; Vannacci *et al.*, 2018; Vannacci *et al.*, 2019), and duality as an emitter and as a receiver (Vannacci *et al.*, 2018; Vannacci *et al.*, 2019).

This study examined whether the photovoltaic effects might be used for monitoring light information in plant-cultivation environments. If some useful information could be acquired, then turned-off LEDs could also be used effectively as sensors for plant-cultivation management. LEDs can be installed proximately to plants (Morrow, 2008) because of their characteristics of low heat radiation and small package size (Schubert and Kim, 2005). For this

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Fig. 1. Relative spectral photon flux densities (a) emitted from 5-mm-diameter LEDs respectively represented as LED₄₆₄, LED₅₀₁, LED₆₃₄, LED₈₄₉, and LED_{455/574} and forward voltage V_F – current I_F characteristics during light emission (b).

reason, LEDs can be installed not only on the ceilings and walls of horticultural facilities but also inside crop canopies (Joshi *et al.*, 2019). If LEDs could be used as light sensors, then acquisition of light distribution information (Ibaraki and Shigemoto, 2013) over a large plantation might become possible. Moreover, an LED might be used as a sensor for acquiring plant information related to optical parameters such as vegetation density.

For this study, open circuit voltages of unimodal spectral LEDs of four types with respective emission peak wavelengths of 464, 501, 634, and 849 nm were investigated when they were irradiated by other external lighting sources. Those LED lights cover the radiation wavelength ranges necessary for plant growth and development. In addition, the open circuit voltage of a white LED with a bimodal spectrum with a primary sharp peak of 455 nm and broad secondary peak of 574 nm was tested. First, we investigated the wavelength range of incident light that induces an open circuit voltage in the five types of LED. Next, the open circuit voltages of the LEDs irradiated with sunlight were measured. Finally, the open circuit voltages induced in the LEDs by incident light transmitted through plant leaves were investigated. Based on these data, we propose to use LEDs, which are usually used as a light source for plant cultivation practices, as light sensors that provide light environment information useful for plant cultivation management.

2. Materials and methods

2.1 LED photovoltaic effects induced by impinging unimodal spectral light

Bullet-shaped, 5-mm-diameter LEDs of five types were assumed to be used as a light source for plant cultivation. Although LED package types have some variations, including surface-mount type which has been distributed commonly in plant cultivation practices, bullet-shaped LEDs were chosen for this study because their electrodes have ease of connectivity with test cables and test bread boards. Their performance as light sensors was tested to elucidate a new role of LEDs when they are turned off. Emission spectra of the five LED types were measured using a spectroradiometer (MS720, Eko Instruments Co., Ltd., Tokyo, Japan) (Fig. 1a). The wavelengths λ_{prS} , which represent the peaks of unimodal spectral photon flux density (SPFD) of four LED types were, respectively, 464 nm (NSPB510AS; Nichia Corp., Tokushima, Japan), 501 nm (NSPE510DS; Nichia), 634 nm (NSPR510CS; Nichia), and 849 nm (TSHG8400; Vishay Intertechnology Asia Pte. Ltd., Tampines, Singapore). The bimodal spectral peaks of a white LED (NSPW510DS-D1; Nichia) were

Fig. 2. Conceptual diagram of current–voltage characteristics of a p-n junction semiconductor.

I_F , I_O , I_L , I_R , and V_{OC} respectively represent the forward current, saturated dark current when a reverse voltage is applied, the generated current that flows through the semiconductor by light irradiation, current that flows in the opposite direction when the semiconductor is irradiated with light, and the open circuit voltage induced by light irradiation.

a 455 nm primary peak and a 574 nm secondary broad peak. Using the values of these emission peak wavelengths, the five LED types are represented as LED₄₆₄, LED₅₀₁, LED₆₃₄, LED₈₄₉, and LED_{455/574}. Figure 1b depicts the forward voltage V_F – current I_F characteristics of the five LED types. The LED₆₃₄ and LED₈₄₉, which emit longer wavelength radiation, have I_F increment at V_F s of less than 2 V, whereas LED_{455/574}, LED₄₆₄, and LED₅₀₁, which emit shorter wavelength radiation, have I_F increment at V_F s of greater than 2 V. The relation between V_F and I_F of an ideal p-n junction diode is given as

$$I_F = I_O \left\{ \exp \left(\frac{qV_F}{kT} \right) - 1 \right\} \quad (1)$$

by the Shockley equation (Shockley, 1949), where I_O is the magnitude of saturated dark current when a reverse voltage is applied to the diode (Fig. 2) and where q , k , and T respectively represent the unit charge amount, Boltzmann constant, and thermodynamic temperature. When the diode is irradiated with light to induce photovoltaic power, current I_R flowing in the opposite direction to I_F becomes

$$I_R = I_L - I_F = I_L - I_O \left\{ \exp \left(\frac{qV_F}{kT} \right) - 1 \right\} \quad (2)$$

by taking the I_R direction as positive (Cuevas *et al.*, 2000). In that equation, I_L is the generated current flowing through the

p-n junction semiconductor by means of light irradiation. I_L is proportional to both the number of photons N having V_{OC} inducible wavelengths and the surface area A of the p-n junction semiconductor die receiving the light (Cuevas *et al.*, 2000). Therefore, accurate light-sensing applications of p-n junction semiconductors usually monitor I_L values (RayChaudhuri and Sen, 2009). However, the I_L values generated in an LED are too diminutive to be measured using conventional and reasonable instruments. The application purpose of this study is to use photovoltaic effects of numerous turned-off LEDs already installed ubiquitously around crops to obtain light information across the plantation. Therefore, measurement of LED voltage is more practical than that of photo-generated current. According to equation 2, the open circuit voltage V_{OC} between the LED electrodes at $I_R = 0$ with incident light becomes

$$0 = I_L - I_0 \left\{ \exp \left(\frac{qV_{OC}}{kT} \right) - 1 \right\} \quad (3)$$

and thereby

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \quad (4)$$

(Cuevas *et al.*, 2000; Shockley, 1949). Using coefficients a and b , equation 4 can be rewritten according to the following equation as the relation between the photon flux density and V_{OC} that can be measured by the growers using conventional instruments.

$$V_{OC} = a \ln (b E_{\text{eff}} + 1) \quad (5)$$

In that equation, E_{eff} is the photon flux density in the V_{OC} inducible wavelength range. The photon to voltage conversion characteristics of LED₄₆₄, LED₅₀₁, LED₆₃₄, LED₈₄₉, and LED_{455/574} can be expressed using equation 5 with experimentally obtained coefficients a and b .

To find the coefficients a and b , we conducted an experiment in which the five type LEDs were irradiated with unimodal spectral artificial light from outside using various other type LEDs. In a dark room, 3-mm-diameter bullet-shaped LEDs of 17 types (Epitex Inc., Kyoto, Japan), respectively having specific wavelength λ_{PE} at each radiation peak were placed respectively close to the spectroradiometer. The emitted SPFD was measured when each maximum rated forward current was applied to the respective 17 LEDs. One of the 3 mm LEDs of 17 types, as an emitter, was faced to one of the 5 mm LEDs as a light receiver. The V_{OC} induced in the 5 mm LED was measured (34401A; Agilent Technologies Inc., California, USA) when the 3 mm LED emitted light (Fig. 3).

2.2 LED photovoltaic effects induced by impinging sunlight

Assuming that LEDs are used for outdoor and greenhouse cultivations, V_{OC} s of the 5 mm type LEDs irradiated with sunlight were measured. During 9:00–12:00 on 20 October 2020, LED₄₆₄, LED₅₀₁, LED₆₃₄, LED₈₄₉, and LED_{455/574} were fixed toward the zenith on the rooftop of a building of Shimane University Matsue Campus. The V_{OC} values of each type LED were measured at 30 s intervals using a data acquisition unit (34972A; Keysight Technologies Inc., California, USA). Sunlight SPFD of wavelengths of 350–1050 nm and

Fig. 3. Three-millimeter diameter LED on the top as the light emitter and 5-mm-diameter LED on the bottom as the receiver facing each other.

photosynthetic photon flux density (PPFD) in the 400–700 nm wavelength range were also measured at 30 s intervals using the spectroradiometer. The sky condition was fine. Assuming that LEDs are installed near crops, the LEDs are expected to receive light that has been transmitted through plant leaves or which was reflected by leaves. To test V_{OC} responses under such conditions, one leaf blade of lettuce (*Lactuca sativa*) was placed over the LEDs and the spectroradiometer at 9:54. The V_{OC} induced by the light transmitted through the leaf and SPFD of the leaf transmitted light were measured.

To confirm the reproducibility of phenomena observed on October 20, V_{OC} s of the LEDs irradiated with sunlight were measured again on the same rooftop on 26 October 2020. The V_{OC} s of the LEDs fixed toward the zenith at 9:00–17:30 were measured at 3 s intervals (34972A). The SPFD and PPFD of sunlight were measured at 60 s intervals using the spectroradiometer positioned proximate to the LEDs. The weather was fine. At 10:22, a lettuce leaf covered the LEDs and the spectroradiometer.

3. Results and discussion

3.1 Open circuit voltage of LEDs irradiated by unimodal spectral light

Table 1 presents V_{OC} s induced in the 5 mm LEDs when they were irradiated with light emitted by one of the 3 mm LEDs of 17 types operating at their maximum rated forward current. The V_{OC} s were induced when excitation light had a shorter wavelength than the inherent threshold wavelength of each 5 mm LED.

Figure 4 depicts SPFDs of the 3 mm LEDs and SPFDs that can be emitted by the receiver-side 5 mm LEDs. Figure 4a depicts the SPFDs of light emitted from the 3 mm LEDs respectively having $\lambda_{\text{PE}} = 387, 408, 445, 494, 525$ nm that induced V_{OC} s in LED₄₆₄ and the SPFD emitted from $\lambda_{\text{PE}} = 594$ nm LED that did not induce V_{OC} in LED₄₆₄. The SPFDs emitted by the 3 mm LEDs with $\lambda_{\text{PE}} = 387, 408, 445$ nm distributed completely on the shorter wavelength side of the LED₄₆₄ spectrum. They induced V_{OC} of around 2.3 V in LED₄₆₄ (Table 1). The spectral distributions of $\lambda_{\text{PE}} = 494, 525$ nm ranged in the longer wavelength side than the LED₄₆₄ spectral peak. The shorter wavelength side of those spectra partially overlapped

Table 1. Specifications of the emitter side 3-mm-diameter LEDs of 17 types and induced open circuit voltage V_{OC} values of the receiver side 5-mm-diameter LEDs of five types.

Emitter LEDs				Receiver LED open circuit voltage V_{OC} (V)				
λ_{PE} (nm)	V_F (V)	I_F (mA)	PFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	LED ₄₆₄	LED ₅₀₁	LED ₆₃₄	LED ₈₄₉	LED _{455/574}
387	3.48	30	829	2.221	2.058	1.407	0.833	2.217
408	3.58	40	1125	2.315	2.122	0.992	0.887	2.359
445	3.40	30	1332	2.310	2.146	1.446	1.017	2.206
494	3.50	30	814	1.552	1.907	1.553	1.020	0.082
525	3.58	30	404	0.024	0.132	1.578	0.963	0.005
594	2.05	40	203	0.000	0.000	1.586	0.860	0.000
614	1.95	50	347	0.000	0.000	1.605	0.972	0.000
644	2.04	40	216	0.000	0.000	1.539	0.870	0.000
678	1.88	50	804	0.000	0.000	1.477	1.083	0.000
700	2.03	50	984	0.000	0.000	0.641	1.094	0.000
743	1.85	70	2414	0.000	0.000	0.002	1.111	0.000
773	1.88	90	3772	0.000	0.000	0.001	1.133	0.000
790	1.71	100	4664	0.000	0.000	0.000	1.149	0.000
822	1.58	100	3598	0.000	0.000	0.000	1.138	0.000
833	1.77	100	3959	0.000	0.000	0.000	1.135	0.000
872	1.60	100	5565	0.000	0.000	0.000	1.068	0.000
937	1.53	100	1720	0.000	0.000	0.000	0.016	0.000

λ_{PE} , emission peak wavelength; V_F , forward voltage applied to the emitter side 3 mm LED; I_F , forward current of the emitter LED; PFD, photon flux density

the LED₄₆₄ spectrum. As the result, low V_{OC} s were induced (Table 1). Because no overlap was found between the $\lambda_{PE} = 594$ nm spectrum and the LED₄₆₄ spectrum, $V_{OC} = 0$ V (Table 1). A V_{OC} value induced by incident light corresponds to the intersection of the I_R curve and the V_F axis when the I_F curve is translated in the negative direction (Fig. 2). For this reason, the V_{OC} value can be greater than 2 V for LED₄₆₄, LED₅₀₁, and LED_{455/574}, but it does not reach 2 V for LED₆₃₄ and LED₈₄₉. Similarly to LED₄₆₄, V_{OC} s were induced in LED₅₀₁ by light irradiation with $\lambda_{PE} = 387, 408, 445, 494, 525$ nm, whereas $V_{OC} = 0$ V by light irradiation with $\lambda_{PE} = 594$ nm (Fig. 4b, Table 1). The spectra of $\lambda_{PE} = 743, 773$ nm ranged in the longer wavelength side than the LED₆₃₄ spectrum (Fig. 4c). The shorter wavelength side of these spectra overlapped the LED₆₃₄ spectrum slightly, inducing considerably low V_{OC} s. The emission spectra of the 3 mm LEDs of 17 types were of the shorter wavelength side or were overlapped with the LED₈₄₉ spectrum. Therefore, they all induced V_{OC} s (Fig. 4d, Table 1). Although the spectral distribution of $\lambda_{PE} = 594$ nm overlapped with the secondary emission peak of the bimodal LED_{455/574} spectrum, it had longer wavelength than the wavelength range of the LED_{455/574} primary emission. For this reason, it did not induce V_{OC} for the LED_{455/574} (Fig. 4e, Table 1). The secondary peak was formed by emission from the package-embedded phosphors, which absorbed the primary emission. The phosphors are separated from the LED die. Therefore, light absorption by phosphors does not affect V_{OC} , even if photons emitted from the 3 mm LED with $\lambda_{PE} = 594$ nm are able to interact with the phosphors. Possible emissions from the phosphors by absorbing the $\lambda_{PE} = 594$ nm light can be expected to have longer wavelengths than 594 nm, which is not sensible in terms of the photovoltaic effect for the LED_{455/574} die.

In this way, when a photon having wavelength shorter than or overlapping with the unimodal 5 mm LED emission spectrum impinges the 5 mm LED, the photon energy exceeding the semiconductor bandgap is transferred to a hole–electron pair (Cuevas *et al.*, 2000). Consequently, V_{OC} is induced in the 5 mm

LED. V_{OC} is not induced if the impinging photon energy is less than the bandgap. This phenomenon is consistent with data reported by Vannacci *et al.* (2019) who presented data of overlapping emission and absorption spectra of an LED. Their spectral data clearly demonstrated the same cut-off at the spectral longest wavelengths, whereas a broader distribution of the absorption spectrum extended to the shorter wavelength side by the Stokes shift (Martin *et al.*, 1999; Yang *et al.*, 1993). Accordingly, the longest wavelength limit of each emission spectrum of the four unimodal LEDs is defined as the voltage-inducible threshold wavelength λ_{th} (Table 2). For LED_{455/574}, which has a bimodal emission spectrum, the spectral shape forming the 455 nm primary-peak is assumed to be approximately symmetrical. Then, the wavelength interval from $\lambda_{PR} = 455$ nm to the shortest-wavelength emission limit is assumed to be as long as the interval from the λ_{PR} to the longest-wavelength emission limit of the primary-peak. The λ_{th} of LED_{455/574} was defined as the longest-wavelength limit of the assumed primary-emission spectrum.

Photons emitted from the 3 mm LEDs having $\lambda_{PE} = 408, 445, 614, 790$, and 408 nm respectively induced the maximum V_{OC} s in LED₄₆₄, LED₅₀₁, LED₆₃₄, LED₈₄₉, and LED_{455/574} (Table 1). Each pair of the 3 mm LEDs and the 5 mm LEDs [i.e. (408 nm λ_{PE} , LED₄₆₄), (445 nm λ_{PE} , LED₅₀₁), (614 nm λ_{PE} , LED₆₃₄), (790 nm λ_{PE} , LED₈₄₉), and (408 nm λ_{PE} , LED_{455/574})] was faced to the other so that the 3 mm LED acts as the light emitter and the 5 mm LED as the receiver (Fig. 3). The radiated photon flux density was changed by regulating the power applied to the 3 mm LEDs. The relation between the effective photon flux density (E_{eff}) having shorter wavelengths than λ_{th} and the induced V_{OC} was found experimentally (Fig. 5). Values of photon flux density emitted from each 3 mm LED were measured using the spectroradiometer positioned near each LED. When the E_{eff} axis was plotted logarithmically, three distinct regions, designated as Zones I, II, and III, were found respectively as representing the V_{OC} conditions of being zero, of sharp inclination, and of saturation. Because V_{OC} s

Fig. 4. Spectral photon flux densities of 3-mm-diameter emitter LEDs (represented by each λ_{PE} values) and of 5 mm receiver LEDs (black solid lines).

(a) LED₄₆₄ and V_{OC} inducible emitter side LEDs excepting $\lambda_{PE} = 594$ nm LED; (b) LED₅₀₁ and V_{OC} inducible emitter side LEDs excepting $\lambda_{PE} = 594$ nm LED; (c) LED₆₃₄ and V_{OC} inducible emitter side LEDs excepting $\lambda_{PE} = 790$ nm LED; (d) LED₈₄₉ and V_{OC} inducible emitter side LEDs; (e) LED_{455/574} and V_{OC} inducible emitter side LEDs excepting $\lambda_{PE} = 594$ nm LED

of the three zones cannot be approximated by a single equation, coefficients a and b that approximate the relation between V_{OC} and E_{eff} were found respectively in each zone by equation 5 (Table 2). The V_{OC} s curves were also plotted on a proportional scale E_{eff} axes (Fig. 5 f–j). The measured V_{OC} values can be approximated by equation 5.

3.2 Open circuit voltage of LEDs irradiated with sunlight

Figure 6 depicts sunlight PPFD and V_{OC} measured on 20 October 2020. Scud cumulus clouds occasionally covered the sun

at around 11 o'clock. At 9:54, the lettuce leaf covered the LEDs and the spectroradiometer, causing the PPFD and V_{OC} values to drop sharply and temporarily. The progress of V_{OC} s was classified into three types: saturated, follow-up, and invariant in response to the PPFD increase over time (Fig. 6a). The V_{OC} s of LED₄₆₄, LED₅₀₁, and LED₈₄₉ were saturated, respectively, at 1.9 V, 1.9 V, and 1.0 V when the PPFD values were greater than $1100 \mu\text{mol m}^{-2} \text{s}^{-1}$. These V_{OC} values were slightly less than the respective saturation voltage values (Fig. 5) obtained by the unimodal light irradiation. The V_{OC} of LED_{455/574} followed the PPFD fluctuation to some degree without saturation. The V_{OC} of LED₆₃₄ remained at a constant value of 1.5 V without being affected by the leaf and cloud cover.

Figure 7 depicts sunlight PPFD, and V_{OC} measured on 26 October 2020. The maximum value of the PPFD was $1345 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 11:43:00. Although it was a sunny day with no visible clouds, V_{OC} and PPFD dropped sharply when the LEDs were covered with the lettuce leaf in the morning and when the sun positioned westerly in the late afternoon, during which time direct sunlight was hidden temporarily behind some university buildings and structures. The V_{OC} s of LED₄₆₄ and LED₈₄₉ were saturated respectively at 1.9 V and 1.0 V, when the PPFD values were greater than $1100 \mu\text{mol m}^{-2} \text{s}^{-1}$. These saturation voltages resemble those obtained during the October 20 experiment. The V_{OC} s of LED₅₀₁ and LED_{455/574} followed the progress of PPFD to some extent without saturation. The LED₆₃₄ V_{OC} saturated at 1.5 V until PPFD decreased to $52 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 16:50 (Fig. 7a). The V_{OC} dropped sharply at sunset. Results show that the LED₆₃₄ V_{OC} can be used for binary discrimination between daytime and nighttime for outdoor cultivation.

Fig. 8 depicts the relation between incident E_{eff} and induced V_{OC} of the LEDs of five types when incident sunlight irradiated the LEDs without any disturbance on 26 October 2020. The relation between E_{eff} and V_{OC} varied depending on the LED type. The V_{OC} – E_{eff} relational functions obtained using equation 5 were drawn in Fig. 8. Coefficients a and b are presented in Table 2. Because the LED₆₃₄ V_{OC} was saturated at $E_{eff} = 40 \mu\text{mol m}^{-2} \text{s}^{-1}$ or greater and the function property changed (Fig. 8c), a and b were found separately for Zones II and III, as in the case of the unimodal light experiments. The deviation between equation 5 and the measured values increased when sunlight became the light source. One possible cause of the deviation is the wavelength dependence of the photovoltaic effects (Filippo *et al.*, 2017; Haydaroglu and Mutlu, 2015; Vannacci *et al.*, 2018; Vannacci *et al.*, 2019). Table 1 shows that LED₈₄₉ induced 0.870 V of V_{OC} with a photon flux density of only $216 \mu\text{mol m}^{-2} \text{s}^{-1}$ by unimodal light irradiation with $\lambda_{PE} = 644$ nm. By unimodal light with $\lambda_{PE} = 387$ nm, LED₈₄₉ induced merely 0.833 V, even though the incident photon flux density was $829 \mu\text{mol m}^{-2} \text{s}^{-1}$. Therefore, the sensitivity of V_{OC} depends on the incident light spectrum. The V_{OC} s were induced by photons having wavelengths shorter than λ_{th} . Even for lights having the same E_{eff} value, the wavelength ranges of included photons differ greatly between unimodal light and sunlight. In the sunlight spectrum with wavelengths shorter than λ_{th} , photons having V_{OC} sensitive wavelengths and photons having wavelengths that are less V_{OC} sensitive coexist. When the proportion of the less-sensitive photons becomes dominant in sunlight E_{eff} , the sunlight induces a lower V_{OC} value than the V_{OC} sensitive unimodal light having the same E_{eff} value as that of the sunlight.

Fig. 5. Logarithmic (a–e) and linear (f–j) plots of the relation between the E_{eff} of unimodal spectral light incident on the 5-mm-diameter receiver LEDs and the induced open circuit voltage V_{OC} .

Curves are fitted using equation 5 with respective coefficients a and b reported in Table 2. LED₄₆₄ (a, f), LED₅₀₁ (b, g), LED₆₃₄ (c, h), LED₈₄₉ (d, i), and LED_{455/574} (e, j) were irradiated by 3 mm LED emissions with respective $\lambda_{\text{PE}} = 408$ nm, 445 nm, 614 nm, 790 nm, and 408 nm.

3.3 Open circuit voltage of LEDs irradiated with light transmitted through plant leaves

Covering the LEDs and the spectroradiometer with a single lettuce leaf decreased PPFD from $1196 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 9:53:30 to $302 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 9:54:00 on October 20 (Fig. 6b). Figure 9a depicts the incident light spectra on the LEDs at 9:53:30 and at 9:54:00. By means of photon absorption by chlorophylls, SPFD decreased sharply at less than 500 nm and around 680 nm. As a result, V_{OC} s of LED₄₆₄, LED₅₀₁ and LED_{455/574} having short λ_{th} s were decreased substantially (Figs. 6b and 10a). In contrast, 73% of the sunlight SPFD was available in the lettuce leaf shadow in the wavelength band of 700–900 nm (Fig. 9a). The transmitted light spectrum was concentrated at 700–900 nm by the lettuce leaf covering. For this reason, the relation between V_{OC} and E_{eff} of LED₈₄₉ was closer to that obtained by

the unimodal light irradiation with $\lambda_{\text{PE}} = 790$ nm (Fig. 5i) than that obtained by sunlight irradiation (Fig. 8d). Behind the lettuce leaf, $927 \mu\text{mol m}^{-2} \text{s}^{-1}$ of E_{eff} (Table 3) irradiated LED₈₄₉. The E_{eff} value was sufficient to saturate V_{OC} (Fig. 5i). Therefore, the LED₈₄₉ V_{OC} was unaffected by the lettuce leaf shadow (Fig. 6b, Fig. 10a). Even in the lettuce leaf shadow, LED₆₃₄ was irradiated with $E_{\text{eff}} = 295 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Table 3), which was sufficient to saturate V_{OC} (Fig. 8c). Accordingly, the V_{OC} value of LED₆₃₄ was unaffected by the lettuce leaf shadow (Fig. 6b, Fig. 10a). At 11:31:00, PPFD decreased to $446 \mu\text{mol m}^{-2} \text{s}^{-1}$ because the sunlight was shaded by clouds (Fig. 6c). The spectral change at this event is presented in Fig. 9c. In the shadow of clouds, the proportion of longer wavelength components decreased to a relative degree. Consequently, LED₈₄₉ V_{OC} was decreased (Fig. 6c, Fig. 10d), whereas no V_{OC} decrease was observed in LED₈₄₉

Table 2. Threshold wavelength λ_{th} of V_{OC} inducible photons and estimated coefficients a and b for fitting experimentally obtained V_{OC} by equation 5 in which E_{eff} values were input as $\mu\text{mol m}^{-2} \text{s}^{-1}$.

			Receiver LED				
			LED ₄₆₄	LED ₅₀₁	LED ₆₃₄	LED ₈₄₉	LED _{455/574}
λ_{th} [nm]			561	590	692	921	506
Unimodal spectral light	Zone I	a	–	–	–	–	–
		b	0	0	0	0	0
	Zone II	a	47.437	0.80763	2.0839	0.36080	0.81813
		b	6.0828×10^{-3}	0.10618	0.10148	4.7529×10^{-2}	0.24247
	Zone III	a	9.5461×10^{-2}	8.9545×10^{-2}	5.6630×10^{-2}	5.6841×10^{-2}	0.10335
		b	68563×10^2	22924×10^2	12605×10^6	125030	74543×10^2
Sunlight	Zone II	a	1.6284	2.0743	1.8321	0.30470	0.55264
		b	3.1406×10^{-3}	1.6834×10^{-3}	2.6813×10^{-2}	8.5194×10^{-3}	1.0274×10^{-2}
	Zone III	a	–	–	7.3592×10^{-2}	–	–
		b	–	–	17392×10^2	–	–

Zones I, II, and III respectively represent ranges with no V_{OC} induction, steep V_{OC} increment, and V_{OC} saturation.

Fig. 6. Transitions of PPFD and LED open circuit voltage V_{OC} measured outdoors on 20 October 2020 (a), effects of shading by a single lettuce leaf (b), and effects of shading by scud cumulus clouds (c). **Fig. 7.** Transitions of PPFD and LED open circuit voltage V_{OC} on 26 October 2020 (a) and effects of shading by a single lettuce leaf (b). The instantaneous shading data (b) were unstable because the leaf swaying in the wind was held by hands.

under the leaf shadow.

Covering the LEDs and the spectroradiometer with a single lettuce leaf at 10:22:00 on October 26 led to PPFD of $270 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 7b). Immediately before that moment, the PPFD on the LEDs at 10:20:00 was $1110 \mu\text{mol m}^{-2} \text{s}^{-1}$. Figure 9b depicts incident light spectra on the LEDs at 10:20:00 and at 10:22:00. Similarly to October 20 data, 73% of sunlight SPFD was obtained behind the lettuce leaf in the wavelength band of 700–900 nm. The V_{OC} s of LED_{455/574}, LED₄₆₄ and

LED₅₀₁ decreased because the photon flux density in the shorter wavelength range decreased considerably, whereas the V_{OC} s of LED₆₃₄ and LED₈₄₉ were unaffected by attenuation of the photon flux density in the lettuce leaf shadow (Figs. 7b and 10b).

At 16:00:00 on October 26, PPFD attenuated to $235 \mu\text{mol m}^{-2} \text{s}^{-1}$ (Fig. 9d) by the sunlight natural decrement. This value was closest to $270 \mu\text{mol m}^{-2} \text{s}^{-1}$ obtained by covering the LEDs with the lettuce leaf. The sky had no clouds at 16:00. Because $E_{eff} = 243 \mu\text{mol m}^{-2} \text{s}^{-1}$ was obtained (Table 3), the

Fig. 8. Relation between E_{eff} of sunlight incident and the open circuit voltage V_{OC} .

Curves were fitted respectively using equation 5 with coefficients a and b reported in Table 2.

(a) LED₄₆₄, (b) LED₅₀₁, (c) LED₆₃₄, (d) LED₈₄₉, and (e) LED_{455/574}

LED₆₃₄ V_{OC} retained saturation (Fig. 8c). The V_{OC} saturation value (Fig. 10c) was almost the same as the V_{OC} obtained at 10:22 in the lettuce leaf shadow (Fig. 10b). Therefore, it is not possible to distinguish from the V_{OC} values of LED₆₃₄ whether the PPFD attenuation is attributable to the solar irradiance decrease or shading by leaves. In contrast, a clear attenuation in the LED₈₄₉ V_{OC} value was obtained when PPFD decreased to $235 \mu\text{mol m}^{-2} \text{s}^{-1}$ at 16:00 by the sunlight natural decrement (Fig. 10c), compared

Fig. 9. Spectral photon flux density (SPFD) of sunlight incident on the LEDs.

(a) SPFD of incident light on the LEDs at 9:53:30 just before covering the LEDs with the lettuce leaf on 20 October 2020, SPFD at 9:54:00 during the covering, and their ratio; (b) SPFD of incident light on the LEDs at 10:20:00 just before covering the LEDs with the lettuce leaf on 26 October 2020, SPFD at 10:22:00 during the covering, and their ratio; (c) SPFD of incident light on the LEDs at 11:29:00 just before the sun was obscured by scud clouds on 20 October 2020, SPFD at 11:31:00 when the sun was obscured by the scud cumulus clouds, and their ratio; (d) SPFD at 16:00:00 on 26 October 2020

to the other LED₈₄₉ V_{OC} value obtained when PPFD was reduced to $270 \mu\text{mol m}^{-2} \text{s}^{-1}$ as the result of lettuce leaf shadow (Fig. 10b). Under natural sunlight conditions, the magnitude relation of V_{OC} s was LED₄₆₄, LED₅₀₁ > LED₈₄₉ irrespective of the sunlight intensity (white bars in Fig. 10). However, the V_{OC} magnitude

Table 3. Leaf shading effects on photon flux density E_{eff} impinged LEDs.

			E_{eff} [$\mu\text{mol m}^{-2} \text{s}^{-1}$]				
			LED ₄₆₄	LED ₅₀₁	LED ₆₃₄	LED ₈₄₉	LED _{455/574}
20 October	Sunlight	9:53:30	641	767	1224	2128	412
	Lettuce	9:54:00	134	182	295	927	48
	Sunlight	11:29:00	846	1014	1621	2820	543
	Cloudy	11:31:00	285	329	474	722	199
26 October	Sunlight	10:20:00	597	713	1137	1981	384
	Lettuce	10:22:00	122	163	265	843	47
	Afternoon sunlight	16:00:00	133	157	243	418	89

Fig. 10. Effects of shading by lettuce leaves on V_{OC} (October 20 a; October 26 b), V_{OC} at 16:00 on October 26 when PPFD was $235 \mu\text{mol m}^{-2} \text{s}^{-1}$, which was the closest measured value to the PPFD at 10:22 under the lettuce leaf shadow (c), and V_{OC} at the moment when sunlight was covered by scud cumulus clouds on October 20 (d).

relation was $\text{LED}_{849} > \text{LED}_{464}, \text{LED}_{501}$ in the shadow of lettuce leaves. Accordingly, the magnitude comparison between the $\text{LED}_{849} V_{\text{OC}}$ and the V_{OC} s of LED_{464} and LED_{501} can discriminate the difference between light attenuation causes, one of which is attributable to natural sunlight attenuation by changes in solar altitude and cloud covering, and the other one of which is attributable to shading by plant leaves.

4. Conclusions

We investigated the light environment information obtained from

the open circuit voltages of the turned-off LEDs. Few studies have reported the potential use of this information in plant cultivation practices. This study clarified that the open circuit voltage reflects the photon flux density around plants. Furthermore, results suggest that LED open circuit voltages can be used to extract characteristics and variations of qualitative light distribution in a cultivation space by taking advantage of numerous LED installations near the plants. An LED with open circuit voltage that saturates at a low photon flux density can be used for binary discrimination between daylight and night. A threshold wavelength of light exists for inducement of the open circuit voltage to an LED. By virtue of this feature, existence of plant leaves between a light source and the LEDs can be detected by comparing the open circuit voltage relations between blue-green range LEDs and NIR LEDs.

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