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A Comparative Study between Phosphor-Converted LED and Color-Mixed LED for Horticultural Applications Based on Power Quality and Lighting Quality

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Abstract: This study aims to identify the advantages and disadvantages of the power quality and light quality of horticultural light produced from the phosphor-converted LED (pcH-LED) compared to the color-mixed LED. The research goal is to elucidate the light characteristics of pcH-LEDs and promote them in indoor cultivation. The light quality and power quality were measured by a spectroradiometer and power analyzer, respectively. The results showed that the pcH-LED exhibited the highest percentage of far-red light and produced the highest PPFD, YPFD, and $P_{eff,}$ with the lowest amount of power consumed. The disadvantage of pcH-LED is that it generated the lowest power factor and showed the current waveform distortion. In conclusion, the pcH-LEDs are appropriate for indoor horticultural applications. They could emit a comprehensive range of light that plants need, from visible (400-700 nm) to far-red (701-780 nm). However, the addition of the power factor correction is required to improve the low power factor problem.

Keywords: phosphor-converted LEDs, color-mixed LED, horticultural application, power quality.

基于电能质量和照明质量的园艺应用荧光转换引领与混色引领对比研究

摘要：本研究旨在确定与混色引领相比，荧光转换引领(多氯联苯-引领) 产生的园艺灯的电能质量和光质量的优缺点。研究目标是阐明多氯联苯-引领的光特性并在室内栽培中推广。光质量和电能质量分别由光谱辐射计和功率分析仪测量。结果表明，多氯联苯-引领表现出最高的远红光百分比，产生最高的 PPFD、YPFD 和佩夫，消耗的功率最低。多氯联苯-引领的缺点是它产生最低的功率因数并显示电流波形失真。总之，多氯联苯-引领适用于室内园艺应用。它们可以发出植物所需的各种光，从可见光（400-700纳米）到远红光（701-780纳米）。但是，需要增加功率因数校正来改善低功率因数问题。

关键词：荧光粉转换引领、混色引领、园艺应用、电能质量。

1. Introduction

The LED artificial light is most commonly used for horticultural applications. This is because LEDs possess various advantages over the classical light source, which includes, but are not limited to, their small size, the ability to produce the spectrum match with the photosynthesis active radiation (PAR) wavelength, good stability, long life span, and their high PAR efficiency [1].

The previous study clearly indicated that the LED artificial light is assembled from an array of single color LED (SCL) such as red(R), far-red (Fr), blue (B), and green (G). The previous authors combined different SCL to form a color-mix LED (cm-LED) array, which could generate the specific spectrum of interest. The light from cm-LED shows better quality than the SCL. Many studies focused on the effects of the light quality of the cm-LED, especially for R, B, W, and Fr, to the morphology and metabolism of horticulture species [2, 3], which may be manipulated to customize the plant growth and development by combining the R (650-665 nm) and B (420-455 nm) LEDs. As a result, higher photosynthetic activity than monochromic LED light was observed [4]. It can be stated that the light quality is related to the specific light spectrum, especially in B, R, and Fr [5]. Some

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studies reported that the R and Fr photon flux ratio is an interesting fact that can also impact the plants' growth and development, yield, and quality [6, 7].

The advantage of the cm-LED artificial light is that it can emit and control the specific spectrum in each wavelength band. It is possible to control the R:B and the R:Fr photon flux ratios. However, many issues are shown to be the disadvantages of panel-type LED artificial light. For instance, the sheer number of LEDs has been proven to be very complicated for the assembly and affects the design complexity of the LED circuit, meaning that separate LED drivers are needed.

Currently, the pc-LEDs for horticultural (pcH-LED) are dominant products in the market. They are fabricated by combining an LED chip and phosphor in a single chip. This product could emit the blue, red, and Fr spectrum. Typically, pcH-LED scan produces the photon flux between 380 nm – 780 nm of wavelength. That is the perfect quality of light that mimics the PAR spectrum. The substitution of the cm-LED that can generate the R, B, UV, and Fr of light by such chip is then possible. Thus, the pcH-LED becomes a simple and convenient alternative to the cm-LED because it has no complex circuit and possesses simple assembly potential, which includes the LED driver on the chip, and can directly connect to the low voltage AC power source.

Artificial LED light uses the AC low voltage grid, with power quality that is of concern. Previous studies reported the comparison of the HPS lamps and LED lighting based on energy conservation, energy consumption, and photometric quality on the road lighting application [8-10]. Uddin reported the power factor and current harmonic distortion from many types of low-wattage LED lamps with and without filter devices for interior lighting applications [11]. Santiti reported comparative studies of the LED lighting and HPS lamp in terms of the power quality and light quality [12]. Comparative studies focusing on the LED for the horticultural application are less common. Previous studies related to the application of pcH-LED for indoor plant cultivation and plant factory system are rather lacking, especially in terms of the power quality and light quality, and hence, are not included in this literature review.

Questions, such as "What are the characteristics of the power quality and light quality of the pcH-LED when compared to mc-LED? Which method is more beneficial and suitable for application in the horticultural domain?", motivated the author to define the experimental study objectives and to compare the power and light quality of the pcH-LED and the mc-LED artificial light. The result of this study should provide integrated knowledge between engineering science and botany and show the advantages and disadvantages of the pcH-LEDs as the light source for the plant factory and other indoor horticultural systems.

2. Material and Method

2.1. Artificial Light Sources

2.1.1. FL Light

The FL light used for the control group is custom-made. The light area (60cm × 60cm) consists of six 18 W, 2600 lm fluorescent warm white lights. The spectrum distribution of the FL grow light is shown in Fig. 1a.

2.1.2. cm-LED Light

This study used a commercial cm-LED horticulture light model UFO180 LED. The authors chose this product because it is well-known for being used for indoor horticulture during study time. The input voltage is 85-220V/50-60 Hz with 27.5 cm × 6.5 cm diameter. It consists of four colors as follows: 28 of R, 28 of B, 2 of UV, and 2 of Fr. Each LED is of 3 W, bringing the total power of 180W (Fig. 1b).

2.1.3. pcH-LED Light

The chip-on-board LED horticulture light YXO-GLC-8001 also was applied in this study. The specifications of the pcH-LED grow light were as follows: Input voltage: 220 V (50 Hz), dimensions: 78 mm × 44 mm × 1.6 mm, power: 20 W, and lighting angle: 120°. The prototype comprised five modules of LEDs connected in parallel. The total power was 100 W. The prototype was installed on an aluminum heat sink with dimensions of 27.5 cm × 27.5 cm × 15 mm (Fig. 1c). The supply voltage was 220 V (50 Hz) and could be supplied directly to the LED chip without the need of an external LED driver.

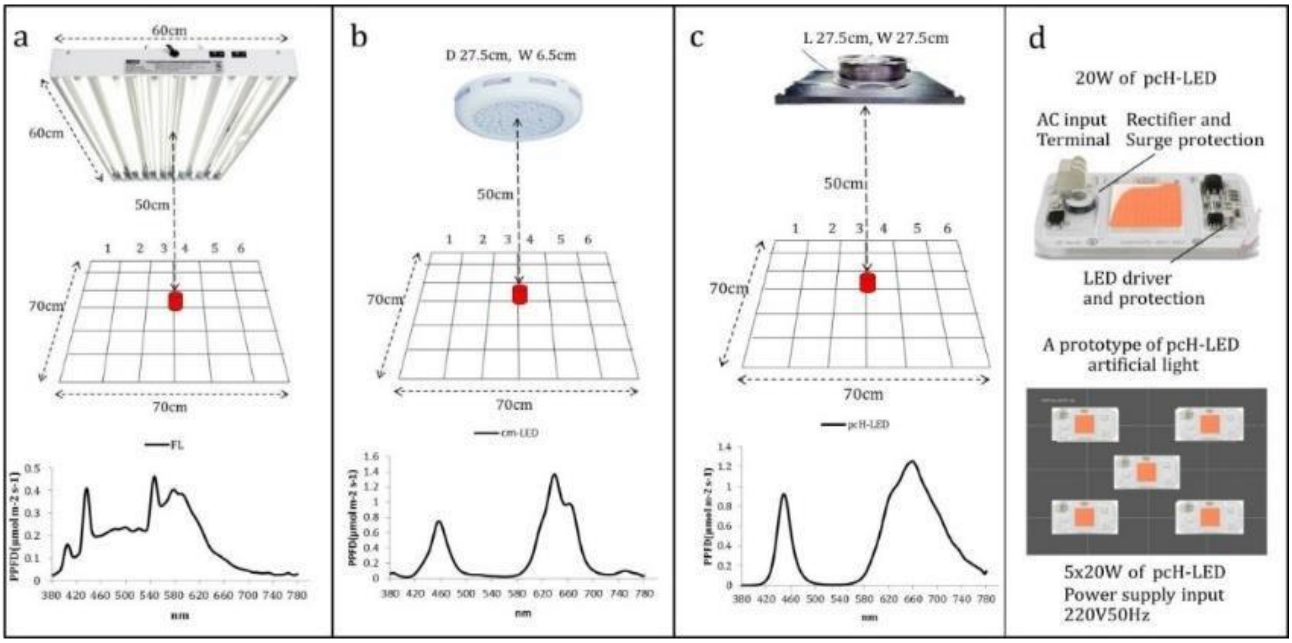

Fig. 1 Three types of artificial light sources: (a) FL, (b) cm-LED, and (c) pcH-LED, spectrum distribution and the measurement point of PPFD on the growth area, and (d) pcH-LED assembly five chips of them on the aluminum heat sink

2.2. Light Quality Factor

2.2.1. Photosynthetically Active Yield Efficacy (PAYE)

The light quality factor refers to the spectrum distribution of the LED light radiation that mimics the PAR spectrum [3, 13]. In this study, light quality includes the specific spectrum distribution between 380 nm and 780 nm and also considered in the terms of PPFD, including the UV to Fr range. The yield photon flux density (YPFD) is the efficiency of using photon flux in photosynthesis, which is used to calculate the PAYE percentage (Eq. (1)) as well as the photosynthetic efficacy (P_{eff}) of different artificial lights [14] (Eq. (2)). The latter factor represents the total amount of photon flux in the PAR spectrum that reaches the canopy of plants. Finally, the uniformity of the photon flux on the growth area was analyzed.

$$\%\text{PAYE} = \frac{YPFD}{PPFD} \times (100) \quad (1)$$

$$\text{Photosynthetic efficacy } (P_{eff}) = \frac{PPF}{Pe} \ (\mu\text{mol j}^{-1}) \quad (2)$$

where PPFD is the photosynthetic photon flux density, YPFD is the yield of PPFD (units in µmol $m^{-2}s^{-1}$), P_e is the electrical source power (W), P_{eff} is the photosynthetic efficacy (µmol j^{-1}), and PPF is the total amount of photosynthetic photon flux in each second (µmol s^{-1}).

2.2.2. Light Uniformity

The uniformity of light on plant canopies is even more important in growing uniform crops herein. The horticultural light industry recommends that light uniformity is ideally in the range of 0.8 to 1 and should be no less than from 0.6 to 1 (dimensionless) [15]. Several methods can be utilized to determine light uniformity, such as the uniformity ratio of illuminance [12] and the non-uniformity of the solar simulator test under IEC60904-9 [16]. Light uniformity can be calculated by first obtaining the minimum and average PPFD. These values can be measured at each point on the plant canopy or growth area (Eq. (3)).

$$\text{Light uniformity} = \frac{PPFD_{\min}}{PPFD_{avg}} \quad (3)$$

where $PPFD_{avg}$ is the average PPFD, and $PPFD_{min}$ is the minimum of PPFD on the plant canopy.

2.3. Power Quality

Power quality indicates the quality of the electrical power that is supplied to the electrical equipment. It typically depends on the type of load. Generally, power quality is good when the passive load is connected to the main supply system, and it be may be poor on the active load. In this section, electrical voltage, current, real power, frequency, power factor, and percentages of harmonic distortion current ($\%THD_i$) and voltage ($\%THD_v$) are emphasized. These parameters were measured and compared for mc-LED and pcH-LED artificial light. The harmonic distortion measurement also was compared to IEC6100-3-2 [11]. The IEC61000-3-2:2018 is concerned with the limitation of harmonic currents injected into the public supply system. This standard is applicable to electrical and electronic equipment (including solid-state lighting) that has a rated input current up to and including 16 A per phase, and it is intended to be connected to public low-voltage distribution systems.

3. Experimentation

3.1. PPFD and YPFD Measurement Procedure

The PPFD and the artificial light spectrum measurements were conducted using a spectroradiometer. The response wavelength range was between 380 nm and 780 nm, the output wavelength pitch was 1 nm, and the optical resolution was 10 nm. The spectrum analysis software was used to analyze the total PPFD, YPFD, peak wavelength, and specific PPFD in each range. The spectroradiometer was placed at the center of the test area in the growth tent at a temperature range of 26 ± 2°C. Measurement data were recorded after 1 min when the light is switched on.

3.2. Light Uniformity Measurement Procedure

In the measurement procedure, the measurement points were divided into 36 equal-sized test positions (6 × 6) on a growth area of 70 cm × 70 cm. Each artificial light was hung at 50 cm above the growth area (Fig. 1a, b, c). The Quantum Meter 3415FXSE model was used. The average PPFD measured in this section was used to calculate the photosynthetic efficacy in Section 3.3. Subsequently, PPFD was measured from each position and calculated by using Eq. (3).

3.3. Power Quality Measurement Procedure

Power quality was measured by using a Fluke 435 power quality analyzer, and all light sources under test were measured using the Fluke i30 current clamp and a personal computer. Signal analysis was performed using the Fluke 430 series power analyzer software. To obtain stable results, each light source was switched on for 10 min before the first measurement was taken. The AC input terminals of the FL, mc-LED, and pcH-LED were measurement points. Each of these terminals was measured thrice on the same day to eliminate measurement errors.

4. Results and Discussion

4.1. PPFD, PAYE, and P_{eff}

The total PPFD (400 nm–780 nm) from FL was 67.36 µmol $m^{-2}s^{-1}$ (Fig. 3). The highest PPFD was obtained from the G light at 32.05 µmol $m^{-2}s^{-1}$ (45%), a B of 20.92 µmol $m^{-2}s^{-1}$ (30%), an R of 14.42 µmol $m^{-2}s^{-1}$ (21%), an Fr of 2.39 µmol $m^{-2}s^{-1}$ (3%), and a UV (380–399 nm) of 1% (Fig. 2(a), 2(d)).

The mc-LED exhibited a total PPFD of 106.75 µmol $m^{-2}s^{-1}$ (Fig. 3), which was greater than the FL by 158%. The highest PPED was obtained for R, with a value of 73.94 µmol·$m^{-2}s^{-1}$ (65%). The PPFD from B was ~27.75 µmol $m^{-2}s^{-1}$ (25%), Fr was 5.55 µmol $m^{-2}s^{-1}$ (5%), and the combination of partial green light and UV light was ~5.04 µmol $m^{-2}s^{-1}$ (4%) and 1.04 µmol $m^{-2}s^{-1}$ (1%), as shown in Fig. 2 (b), 2 (d). Lastly, the total PPFD from the pcH-LED equals 130.76 µmol m-2s-1 (Fig. 3), which is higher than FL by 197 %. In this case, the readout shows the R of 96.12 µmol m-2s-1 (60% of total) and Fr of 28.52 µmol $m^{-2}s^{-1}$ (18%). The PPFD from B is about 28.16 µmol $m^{-2}s^{-1}$ (18%), and the PPFD from G and UV showed no significant difference from the mc-LED (Fig. 2c). The pcH-LED could produce the highest PPFD when compared to the mc-LED and FL.

In summary, the pcH-LED could emit the G and R spectrum distribution with values close to mc-LED of Fig. 2 (c), 2(b) and different from Fr.

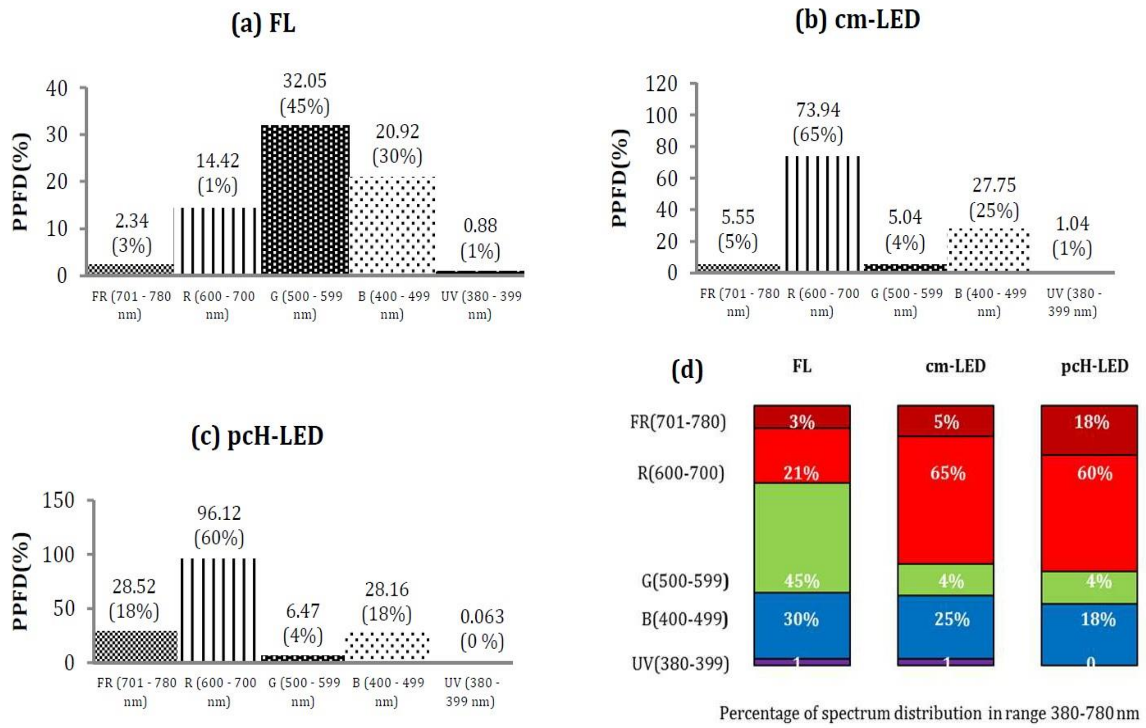

Fig. 2 (a) PPFD of FL in Fr to UV, (b) PPFD of mc-LED, (c) PPFD of pcH-LED, (d) The percentage of spectrum distribution of FL, mc-LED, and pcH-LED

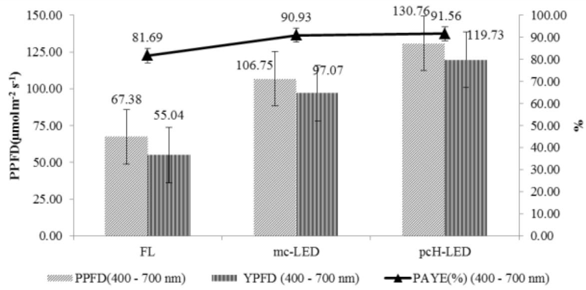

Fig. 3 Comparison of the total PPFD, YPFD, and photosynthetically active yield efficacy (PAYE, %)

According to the results, pcH-LED generated 18%, which is higher than mc-LED of 5%. The pcH-LED could promote the highest PPFD when compared to mc-LED and FL. The percentage of spectrum distribution in the range of 380 nm - 780 nm from pcH-LED is fairly close to mc-LED (Fig. 2(d)), but very different from FL in terms of the PPFD under G and Fr. The pcH-LED could emit the R of 60% of the total, Fr of 18%, and B of 18%. From this result, the pcH-LED exhibited light quality close to LED light quality. This is in accordance with Samuoliene et al. [5], who reported the R light, Fr, and B light at 16%, 25%, 33%, respectively for mustard, beet, and parsley growth. The microgreens' growth exhibited the increase of several carotenoids and lutein. Moreover, the obtained results are in accordance with the study of Chung, who reported that orchids revealed greater leaf expansion and number, chlorophyll content, fresh and dry weight under R light with B light and Fr than monochromic R and B light [17]. According to the report of Bugari et al. [18], "nutritional quality varied among species, and higher antioxidant compounds were found in red basil on vermiculite and jute" under red, blue, and infrared LED. Watjanatepin [19] reports that Fr radiation from pcH-LED has positive effects on crop quality. It could promote the highest fresh weight, perfect leaf size, and nice leaf color of the Butterhead lettuce, Cos lettuce, Red oak, and Green oak lettuce. The author's results were also confirmed by the report of Park and Runkle, who indicated that if the Fr is increased, the whole plant and net assimilation of many kinds of flowers could also increase [6]. The PAYE from FL is the lowest at 81.69% compared to 90.93% from mc-LED and 91.56 % from pcH-LED (Fig. 3). The height of PAYE indicated that the plants could receive and absorb the PPFD to contribute to the photosynthetic activity. This is in accordance with the report of Darko, where the LED artificial light demonstrated the maximum photosynthetic active radiation efficiency between 80%-100% [1].

Table 1 indicated that the P_{eff} of the pcH-LED is about 1.48 μmol j^{-1}. The P_{eff} from mc-LED is equal to 0.82 μmol j^{-1} and 0.14 μmol j^{-1} from the FL. This study demonstrated that the FL artificial light consumed too much power, at 237.60 W, and has a low ability to convert electrical power to PPFD. Therefore, the FL is not appropriate for the horticultural system in terms of energy efficiency. The pcH-LED artificial light consumed the lowest power of 34.40 W and converted that power to the 101.78 μmol m^{-2} s^{-1} of PPFD (Table 1). In the case of mc-LED, it consumed 53.40 W of power and converted to 87.25 μmol m^{-2} s^{-1} of PPFD. The mc-LED and pcH-LED showed the highest P_{eff} of 0.82 μmol j^{-1} to 1.48 μmol j^{-1}, but the results are not in accordance with the study of Pattison. In his study, he indicated the P_{eff} of 3.1 μmol j^{-1} to 4.7 μmol j^{-1}. This difference may have been caused by the luminous efficacy of the phosphor-converted white LED, which allowed Pattison to obtain higher values than this study. Namely, the values were about 133 lm/W to 169 lm/W [14], which allowed the P_{eff} to reach higher values. The LED that was used in this experiment has a luminous efficacy of about 50-70 lm/W. However, this experimental result demonstrated the P_{eff} close to the LED-based horticultural lighting testing report of 1.8 μmol j^{-1} [20]. In terms of energy saving, the appropriate type of artificial light source such as LED (pcH-LED or mc-LED) must be carefully chosen.

Table 1 Summary of the measurement and calculated results of the photosynthetic efficacy (P_{eff}) and the light uniformity of the artificial light sources in the experiment

Light sources	$PPFD_{avg}$ (μmol m^{-2} s^{-1})	P_e (W)	P_{eff} (μmol j^{-1})	$PPFD_{min}$ (μmol m^{-2} s^{-1})	$PPFD_{max}$ (μmol m^{-2} s^{-1})	Light uniformity
FL	65.97	237.60	0.14	60.00	70.00	0.91
mc-LED	87.94	53.40	0.82	65.00	111.00	0.74
pcH-LED	101.78	34.40	1.48	73.00	132.00	0.72

The obtained results are confirmed by the report of Singh [13], where the LED consumed 25% of the energy of the traditional lamp. Horticultural lighting needs to offer energy-efficient and ecologically sustainable light sources adapted to different requirements of the consumers. LED with embedded drive chips could provide operation flexibility, reliability, efficiency, controllability, and intelligence to the horticultural industry. The application of LED light for the horticultural system depends on the cost of the optical output per watt and their conversion efficiency [1].

4.2. Light Uniformity

The authors found that the light uniformity of the FL is the best at 0.91. The measured minimum and average PPFD is about 60 μmol m^{-2} s^{-1} and 65.97 μmol m^{-2} s^{-1}, respectively (Table 1). This could be because of the long cylindrical and tubular shape of the FL, which could help emit stable light intensity, resulting in the

PPFD distribution on the growth area with good uniformity.

The cm-LED and pcH-LED could produce higher PPFD than FL, but the light uniformity is worse than that of the FL. The measured results demonstrated that the light uniformity of cm-LED is about 0.74 and 0.72 for pcH-LED (Table 1). The pcH-LED generated the highest PPFD (132 μmol $m^{-2}s^{-1}$) (Table 1) at the center of the growth area (Fig. 4c) with decreasing values towards the corner of the growth area. The cm-LED has the same result as the cm-LED, but the PPFD is lower (111 μmol $m^{-2}s^{-1}$) (Table 1), as shown in Fig. 4(b). Fig. 4(a) indicated that the best light uniformity was from the FL.

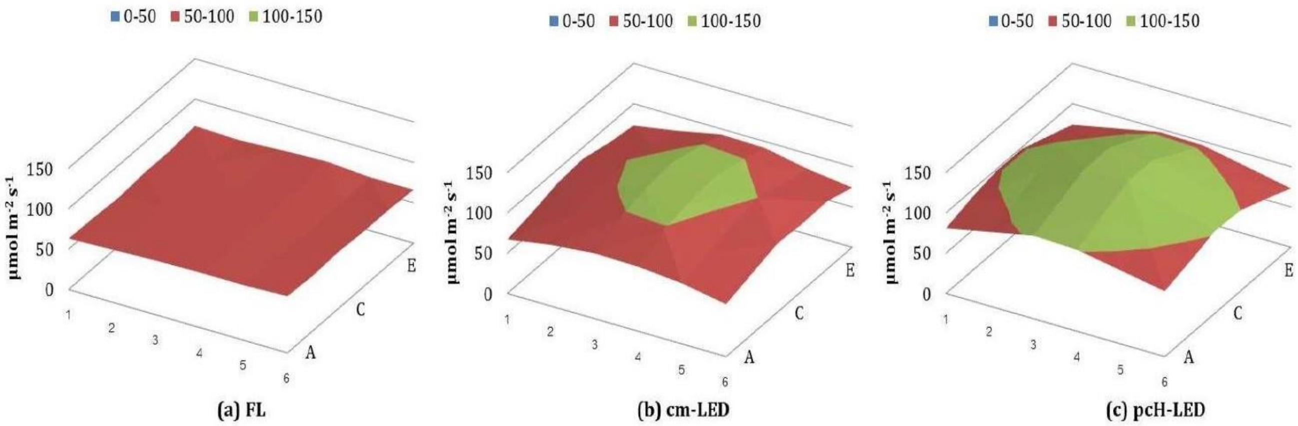

Fig. 4 Comparative results of the light uniformity of the artificial light sources 50 cm above the plantation area in the experiment

The PPFD uniformity testing from the LED artificial light is between 0.72-0.74. It has been shown to have positive effects on the growing uniformity of the crops [20]. Many previous studies exhibited the testing results of the light uniformity of LED street lighting systems and comparing those values to the standard [8, 12, 21]. However, there are no known studies that tested the light uniformity of the LED horticultural lighting. Nonetheless, the manufacturer tests many LED products to determine the PPFD, P_{eff}, wattage, PAR efficacy, reliability, efficiency, daily light integral (DLI), and power quality. In summary, our experimental results showed that the light uniformity from FL, cm-LED, and pcH-LED are appropriate for the application as the horticultural lighting system.

4.3. Power Quality Results

4.3.1. Power and Power Factor

In Table 2, the real power of the FL is 248.10 W with a leading PF of 0.74, whereas the cm-LED has a lower real power requirement of 53.40W with a lagging PF of 0.46. The pcH-LED consumed the lowest real power at 34.40W, with a lagging PF of 0.35. This result confirmed that the LED can save 78% to 86% of power consumption, in comparison with the FL. This finding is in accordance with Lee's report: X-H wherein the B and R LED combination light source could save 86.1% energy when compared to the compact FL [9].

Table 2 Summary measurement results of power quality of the artificial light sources in the experiment

Lamp types	Voltage (V)	Current (A)	Frequency (Hz)	Real power (W)	Reactive power (VAR)	Apparent power (VA)	Power Factor (PF)	THD_i (%)	THD_v (%)
FL	226.3	1.47	49.97	248.10	-225.10	335.00	0.74 leading	3.20	1.00
cm-LED	229.00	0.51	49.94	53.40	104.40	117.30	0.46 lagging	3.80	1.10
pcH-LED	224.70	0.45	49.98	34.40	93.20	99.40	0.35 lagging	10.90	1.10

The FL consumed more real power than the cm-LED and pcH-LED, while the P_{eff} and average PPFD of the FL was lowest. Therefore, the FL is improper for application in the cultivation of plants, because the P_{eff} is the inverse of the real power (Tables 1 and 2). Though FL resulted in the highest PF (0.74 leading), it could generate the highest reactive power (225.10Var) in the low voltage grid, when compared to the cm-LED (104.40Var) and pcH-LED (93.20Var). In terms of the PF, a study reported LED street lighting as having 121W, at 0.97 PF lagging [12]. This indicated a perfect LED lamp, with low losses and high energy efficiency. Our study exhibited medium wattage and low PF of LED horticultural lighting, in comparison to Santiti's study. This could be because of the different properties of the LED driver in the pcH-LED and the cm-LED. Ideally, there should be no power factor correlation (PFC), however, the LED street light driver includes a PFC converter, which can increase the power factor from 0.90 to 0.98. Uddin reported that the testing of twelve different samples of low wattage LED lamp (3W-10 W) showed a PF between 0.48-0.89 lagging [11]. This study shows slight differences in the PF, when compared to our study. The LED driver for the medium-to-low wattage LED is a low-cost driver. This type of driver is commonly very small and includes an LED chip that can produce low PF.

The low PF of the electric load could produce negative effects on the transmission line, such as increasing power losses in the power transformer, transmission line, and the generator. Three artificial lighting types in this study supplied the reactive power to the AC grid with a low PF. It is of particular importance to look at the power factor correction technique in order to increase the PF close to unity.

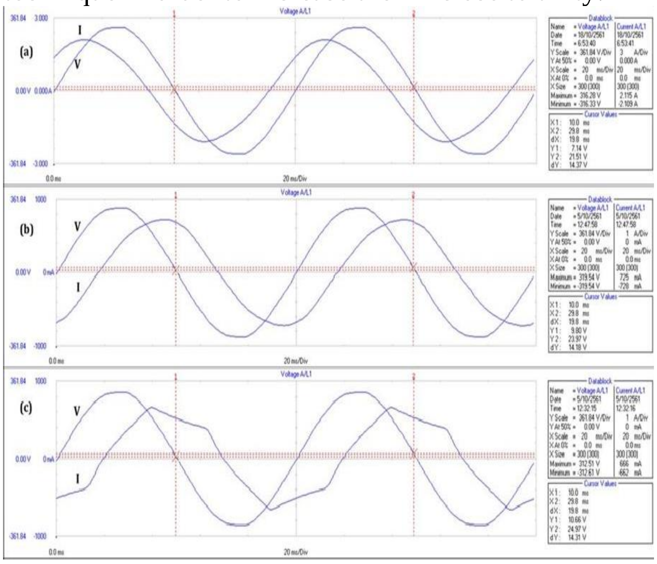

Fig. 5 The voltage and measured current waveform of the (a) FL tube lamps (6 × 20 W), (b) cm-LED (180 W UFO type), and (c) pcH-LED (5 × 20 W)

Fig. 5 can be used to evaluate the characteristics of the power quality in terms of waveform distortion. It can be clearly observed that the voltage waveforms of the FL, cm-LED, and pcH-LED are not distorted. But the current waveform of the pcH-LED (Fig. 5c) shows a sinusoidal distortion, which is a heavier distortion than the current waveform of FL and cm-LED. The current waveform distortion of the pcH-LED exhibited a high value of THDi, which is equal to 10.90%, but the THDi of the FL and cm-LED are still low at 3.20% and 3.80%. The closest result of the 121W LED streetlamp with a PF of 0.97 has a THDi of 13.7% [12]. The current wave form distorts from the fundamental sinusoidal, but the phase angles of the current and voltage waveform are in phase. The distortion of the current wave form depends on the AC filtering method. The active filter will have lower waveform distortion than the passive filter.

4.3.2. Harmonic Current Result

Fig. 5 shows the AC waveform obtained from the three types of artificial light sources. The relative harmonic currents are presented in Table 3. The pcH-LED generates the highest levels of THD_i when compared to the others (Table 2). Table 4 shows the harmonic level under IEC61000-3-2 and the measured results of the harmonic current at the harmonic even number from the light sources. The results show that all artificial light sources are acceptable under the IEC61000-3-2 standard. Although the cm-LED and pcH-LED contain the LED driver (non-linear load) with the filter circuit, that can cause a low THD_i and harmonic current in all harmonic numbers. The FL indicated the lowest THD_i in all harmonic numbers (n = 3, 5, 7, 9, 11..29) because the FL used the choke ballast with the capacitor to operate the lamps. The choke ballast and capacitor are the linear loads, and they will subsequently produce a low percentage of THD_i at about 3.2%.

Table 3 The harmonics current measurement results of the artificial light sources compared to the IEC61000-3-2

Items	Harmonic (%)					
	3rd	**5th**	**7th**	**9th**	**11st**	**THDi**
IEC61000-3-2	30xPF	10	7	5	3	
FL	3.2	0.4	0.2	0.1	0.1	3.2
cm-LED	3.6	1.1	0.5	0.1	0.3	3.8
pcH-LED	8.2	6.6	1.6	2	0.5	10.9

Table 4 Summary of the advantages and disadvantages of artificial light under test

Parameters		Artificial light		
		pcH-LED	**cm-LED**	**FL**
Light Quantity	PPFD	Highest	High	Lowest
	PAYE	Highest	High	High
	P_{eff}	Highest	High	Low
Light Quality	Light uniformity	Fair	Fair	Good
	% of R-Fr	Highest	High	Lowest
	% of B	Low	Low	Low
	% of UV	Zero	Very low	Very low
Power Quality	Real power	Lowest	Low	Highest
	Power factor	Lowest	Low	Highest
	THDi	Accept	Accept	Accept
	THDv	Accept	Accept	Accept
	Current distortion	High	Low	Low

For this reason, the FL was able to exhibit the highest PF of 0.74 and the lowest total current harmonic distortion. The cm-LED generated the THDi of 3.8%, and the pcH-LED exhibited the highest percentage of THDi at 10.9%. This study shows the percentage of THDi from the LED lighting (even for the cm-LED and pcH-LED) at a low value from 3.8% to 10.9%. These values are lower than the LED test from the report of Uddin (30.94% to 174.3%) and are unacceptable according to the IEC61000-3-2 standard. The low values could have been because the LED lamp with the active filter will produce low THDi, and without the filter, it will produce the THDi of over 100% [10]. The relative harmonic content of FL, cm-LED, and pcH-LED are as shown in Table 3. The THDi from the pcH-LED type presented the highest percentage of THDi in all odd harmonic numbers compared to the cm-LED and FL. In summary, the THDi generated from FL, cm-LED, and pcH-LED were not at a high level and acceptable according to the IEC61000-3-2.

From the experimental results of the FL, cm-LED, and pcH-LED, it was found that the input harmonic voltage is very low. This indicated that the voltage has fundamental frequency components only, so their real powers are generated by fundamental frequency currents similar to the real power result of cm-LED. The real power result of cm-LED is about 55% higher than pcH-LED, although the harmonic current of pcH-LED is higher than cm-LED. When considering the PF component, it was found that the PF of pc-LED is about 31% less than the PF of cm-LED. Observing the voltage and current waveforms in Fig. 5b and 5c, the phase angle between the voltage and current of the fundamental frequency ($\theta_1 - \phi_1$) is only slightly different, resulting in similar values of DPFs. On the other hand, the PF of pcH-LED is lower than the PF of cm-LED because its DPF is small due to the pcH-LED's high harmonic currents. However, the PF will be significantly improved by increasing the DPF.

4.3.3. Advantages and Disadvantages

The advantages and disadvantages of LED horticultural lighting compared to FL lighting in terms of light quantity, light quality, and power quality is summarized in Table 4. The pcH-LED has more advantages than the cm-LED and FL in terms of light quality, resulting in the highest percentage of Fr. The pcH-LED exhibits the highest PPFD, YPFD, and P_{eff} light, while consuming the lowest amount of power. Finally, pcH-LEDs do not produce UV light, while cm-LEDs and FLs radiate UV light at very low levels. The emission of UV light is of particular concern, as it can have negative effects on human eyes and skin. However, the disadvantage of pcH-LEDs is that they generate the lowest PF and cause current waveform distortion. The light uniformity of FL lighting is better than that of pcH-LEDs and cm-LEDs because of the lamps, while light uniformity from cm-LEDs and pcH-LEDs is only fair. FL lighting exhibits perfect power quality when compared to the others. This means that pcH-LEDs present more advantages than cm-LEDs and FLs. Therefore, pcH-LEDs can be used as a light source for horticultural applications with additional power-factor correction techniques. However, this may increase the initial cost of the artificial light system.

5. Conclusion

Both pcH-LEDs and cm-LEDs can emit the spectrum distribution that supports photosynthetically active radiation received by the plants, but pcH-LEDs exhibit a higher Fr spectrum than cm-LEDs. The pcH-LED emits a broadband wavelength of light in accordance with the needs of the plants, including visible spectrum (400 – 700 nm) to infrared spectrum (701–780 nm). The pcH-LEDs present more advantages than cm-LEDs and FLs in regards to light quality, resulting in the highest PPFD, PAYE, P_{eff} and the percentage of R and Fr spectrum, and produce no UV radiation.

Moreover, the pcH-LED consumes the lowest real power. The THD_i and THD_v levels are acceptable in the IEC 61000-3-2. The disadvantage of pcH-LEDs is that they exhibit the lowest power factor. In summary, the pcH-LED is the most interesting choice for indoor horticultural application. It could reduce the complexity of circuit assembly as well as energy consumption.

The limitation of this study is that the number of samples (pcH-LED chip included driver unit) in the online electronics market at the time of the author's research was very small. The chip used as an example in this study is probably the first LED chip that does not have a power-factor correction circuit. This may be due to the fact that the power factor analysis of pcH-LEDs is limited and should be improved.

Finally, development of pcH-LED technology continues, and new types of chips may emerge in the near future. Further study is needed.

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