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Visual and melanopic performance of a tropical daylight-mimicking lighting: a case study in Thailand

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ABSTRACT

This paper designed and developed a tropical daylight-mimicking lighting system based on photometric, radiometric and International Commission on Illumination (CIE) standard melanopic performances from natural lighting cycles in Thailand. Spectral power distribution (SPD) during daylight in summer and winter were recorded to create a dynamic artificial lighting system that best matches the natural daylight characteristics. Two set-ups light emitting diode (LED) (LED-A and LED-B) were screened, developed, validated and compared with different chromaticity layouts of the correlated color temperatures (CCTs) allocated on Planckian locus and later converted to x-y co-ordinates in a chromaticity diagram. Based on CCT and Duv deviations between two developed setups, LED-A could mimick circadian points on the chromaticity diagram better than LED-B did. CCT and Duv values of LED-A (δCCT=3.75% and δDuv=17.36%) can match closer to the daylight than those of LED-B (δCCT=5.0 % and δDuv=56.84%). For CIE-standard melanopic performances (melanopic efficacy of luminous radiation (mELR), melanopic equivalent daylight (D65) illuminance (mEDI) and melanopic daylight efficacy ratio (mDER)), LED-A is suitable to use indoor with averages of 1.16 W·lm-1, 236 lx and 0.84, respectively, while LED-B is good to use outdoor with averages of 1.53 W·lm^{-1}, 266 lx and 1.06, respectively. The proposed design can be used as a guideline to establish a daylight-mimicking LED lighting system from actual measurement data.

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1. INTRODUCTION

Natural light is characterized by considerable variability in terms of quantity, direction, and spectral power distribution (SPD). The variability is primarily due to the time of day, but also meteorological conditions, latitude, orographic, or urban contexts. The SPD of natural light changes significantly during the day, from dawn to dusk, and also varies due to levels of cloud cover that can be disturbing on its intensity by atmospheric mixtures of any polluted particles and conditions. Depending on parameters mentioned above, the variability of natural daylight in outdoor areas can range from a level of <1,000 lx in the winter (heavily overcast sky) to 150,000 lx in the summer (clear sky) [1]–[3]. The correlated color temperature (CCT) is commonly used to provide color quality of lighting products. Duv, another term used to describe the distance and direction of color shift from the Plankian locus. CCT and Duv are often used to inform the lighting property. They can also vary considerably from sunrise to sunset daily. Light is one of the most significant external factors which influences the human circadian system that may yield an impact on human physiological functions [4]. Importantly, periodic exposure to light leads the human mind and body to anticipate certain daily activities and promotes periodic variations in biological activities [5]. Lighting directly influences the performance of visual tasks, called "visual effects", by causing critical details of tasks to be more or less visible [6]. The latter effect of light on human perception called "non-visual effects" which affect the human body by influencing physiological process through the human nervous system. There are a two major categories of lighting parameters indicating to vision and circadian performances of light sources as shown in Table 1. The visual performance such as color rendering index (CRI), luminous efficacy of optical radiation (LER) and luminous efficiency (LE) are used to indicate the effectiveness of light source for vision effects. The circadian performances such as circadian stimulus (CS) and circadian light (CL_A) [7] are now non-standard circadian matric values (that will not be considered here). By evolution of the non-visual study of light, CIE recommends to use the new standard CIE S 026/E:2018 and proposes α-opic irradiance as a standard term that related to melanopic irradiance [8]. Therefore, this work regards to the lighting matrices related to the non-visual effects based on the melanopic function including the melanopic equivalent daylight (D65) illuminance (mEDI), the melanopic efficacy of luminous radiation (mELR) and the melanopic daylight efficacy ratio (mDER), which correlate with the circadian radiation [8].

Table 1. Key parameters for the vision and circadian performance of light sources

Parameters	Equations	
Vision performance		
Luminous efficacy of optical radiation (LER) [9]	$\text{LER}\ (\text{lm}\cdot\text{W}_{opt}^{-1}) = \frac{683\ \text{lm}\cdot\text{W}_{opt}^{-1} \int_{\lambda=380}^{780} S(\lambda)V(\lambda)d\lambda}{\int_0^{\infty} S(\lambda)\, d\lambda}$	(1)
Luminous efficiency (LE) [10]	$\text{LE}\ (\text{lm}\cdot\text{W}_{elect}^{-1}) = \frac{683\ \text{lm}\cdot\text{W}_{opt}^{-1} \int_{\lambda=380}^{780} S(\lambda)V(\lambda)d\lambda}{P_{elect}}$	(2)
CIE-standard melanopic (circadian) performance		
Melanopic irradiance (E_{mel}) [8]	$E_{mel}\ (\text{W}\cdot\text{m}^{-2}) = \int_{\lambda=380}^{780} S(\lambda)S_{mel}(\lambda)d\lambda$	(3)
Melanopic efficacy of luminous radiation (mELR) [8]	$\text{mELR}\ (\text{lm}\cdot\text{W}^{-1}) = \frac{E_{mel}}{E_V}$	(4)
Melanopic equivalent daylight (D65) illuminance (mEDI) [8]	$\text{mEDI}\ (\text{lx}) = \frac{E_{mel}}{K_{mel\text{-}ELR}^{D65}}$	(5)
Melanopic daylight (D65) efficacy ratio (mDER) [8]	$\text{mDER} = \frac{\text{mELR}}{K_{mELR}^{D65}}$	(6)

In the early 2000s, the visible-spectrum light emitting diode (LED) illumination has been used pervasively and was rapidly replacing conventional lighting systems, particularly as building owners replace their ageing lights [11]. The design of artificial lighting in the last century using LEDs has focused on improving the quality of mankind's living and working environments. The optimal design goals of an artificial lighting system should synchronize with natural light as much as possible. The lighting systems should be aligned with concepts such as equity, flexibility, simplicity, perceptibility, fault tolerance, reduced physical effort, accessibility, and the ability to adapt to a range of physical sizes and spaces [12], [13]. Thus, lighting technology research must endeavour to fully investigate circadian metrics, leading to the design of circadian lighting control frameworks that provide the human health benefits and well-being that the research has postulated [14]. Bohar *et al.* [15] suggested that in the use of LEDs to simulate the solar circadian lighting, the efficacy and benefits of spectral-temporal based lighting on humans should firstly be elucidated. This required data including solar angle and intensity around those times of day near natural sunrise and sunset [15]. To design a personalized lighting for circadian health improving, the reproducing light should be provided fewer biological effects and exposure time of intervention [16], optimal non-visual parameter [17]–[19], short wavelength environments [20], Shishegar *et al.* [18] demonstrated that the lighting condition in the living rooms of healthy users was a significant environmental element affecting their subjective and objective sleep quality. A whole-day ambient lighting scheme with varying illuminance levels and CCTs that provide a blue-enriched high-intensity daytime lighting and yellow-dimmed evening lighting could significantly improve several objective and subjective metrics of sleep [18]. However, the study on a design of a daylight mimicking system have not been done in Thailand, a tropical country in South-East Asia.

Therefore, this research aimed to study the natural lighting patterns under the clear sky condition in Thailand with the goal of developing an artificial lighting system with daylight patterns that would provide improved visual and living environments. A tropical daylight-mimicking LED lighting system was analysed through various parameters in lighting qualities and circadian (melanopic) matrices as shown as the framework of this study in Figure 1. Figure 1(a) shows the photometric/radiometric properties and the standard melanopic performances of a daylight pattern for a seasonal round year (mid-summer and mid-winter) in Thailand were evaluated to be used as a tropical daylight model. The color matrix of the obtained lighting data was converted to red, green, and blue (RGB) coding for further compiling as shown in Figure 1(b). The screening and selection of LEDs process was conducted using the RGB-LED input software to find effective LEDs to be used in the daylight mimicking steps as shown in Figure 1(c). The compatible LEDs should have the RGB coding compiled in order to validate the tested LEDs from 3,000-10,000 K the x-y co-ordinates on the Plankian's locus and the standard locus of the artificial lights (ANSI, 2,000). Another selection criterion is Duv of the emitted-lights should be within the area of +0.048 from the Plankian's line. This primary criterion was proposed for the candidate LED to be used in the next steps of selection that based on melanopic performance. The evaluation of visual and melanopic performance of LEDs for mimicking of a tropical daylight was conducted by using the tropical daylight database for RGB codes compiled by the RGB-LED input software as shown in Figure 1(d). The new CIE standard for non-visual melanopic parameters included m-ELR, m-EDI and m-DER was used as a criterion for evaluation of LEDs. This study sought to promote further evolution by integrating the science and engineering knowledge regarding biorhythmics into light management and control technologies, thereby opening up new scenarios in lighting systems for health.

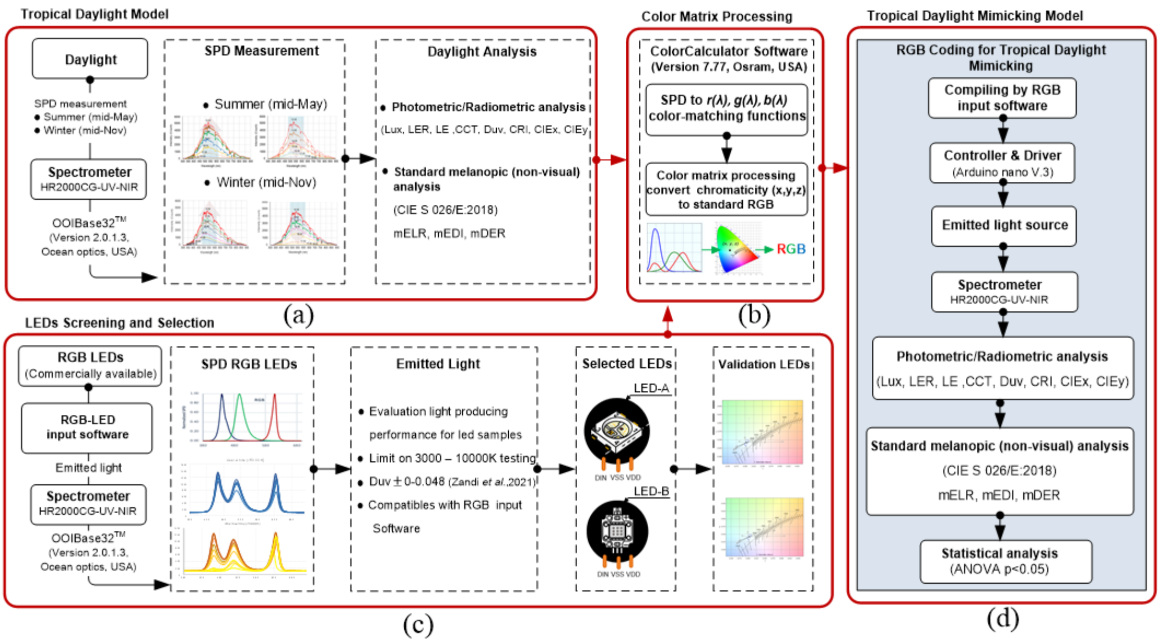


Figure 1. Framework for a tropical daylight mimicking and melanopic performance evaluation (a) analysis of a daylight pattern in Thailand, (b) the color matrix processing, (c) the screening and selection of LEDs, and (d) the evaluation of visual and melanopic performance of LEDs for mimicking of a tropical daylight

2. METHOD

2.1. Analysis of spectrometric properties of circadian light

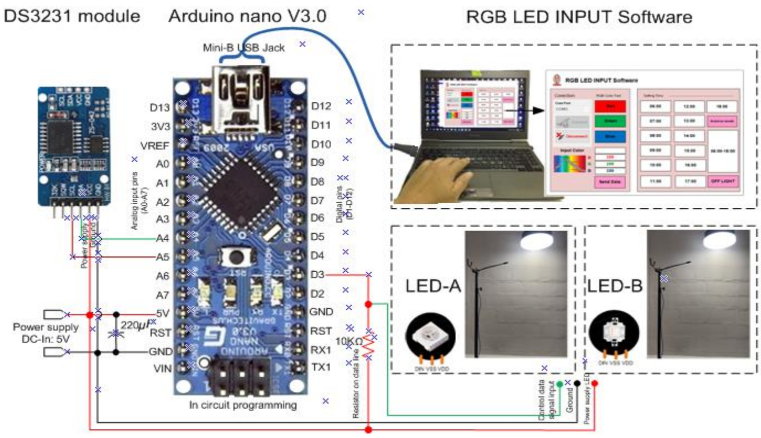
To develop a daylight mimicking system, this study firstly investigated the light spectrum of normal daylight. The experiment was conducted during daytime hours at the northeastern part of Thailand, Kosum Phisai District, Maha Sarakham Province (latitude 16.288505944°, longitude 103.117675781°). Following sunlight characteristics were recorded under clear-sky weather scenario conditions for five days at specified daytime hours (between 06:00 and 18:00) during summer and winter months. SPDs, CCTs (K), illuminance levels (lx), and irradiations (mW·cm^{-2}) were recorded.

Spectral intensities were measured using a high-resolution spectrometer (Ocean Optics, model HR2000CG-UV-NIR, USA), which was calibrated with standard commercial lights. The visible range used was 380-780 nm with average step of 0.5 nm with repeated 200 times per measurement. The spectrometer's signal-to-noise ratio was set at 300:1. The spectrometer also had a built-in feature useful for calculating color space x-y co-ordinates, which in turn were used to calculate CCTs. A laptop PC was used to record real-time data and spectral control by OOIBase32^{TM} software (version 2.0.1.3, Ocean Optics, USA). The spectral measurement was adapted to be in line with CIE (1994) [21]. Measurements were specified to an observation with a vertical aperture angle of 10 degree [21], [22]. A multi-LED light meter (Tenmars, TM-209M, Taiwan) with a maximum measuring range of 400,000 lx was also used for parallel recordings. To minimize measurement errors due to environmental factors, the experiment took into account weather forecasts and recorded instrument reading only on clear-sky days, avoiding weather conditions, such as clouds, rain, and high relative humidity (%RH), that could cause distortion in the readings [23]–[25]. Light sources were also analysed according to visual and melanopic performances mentioned in Table 1.

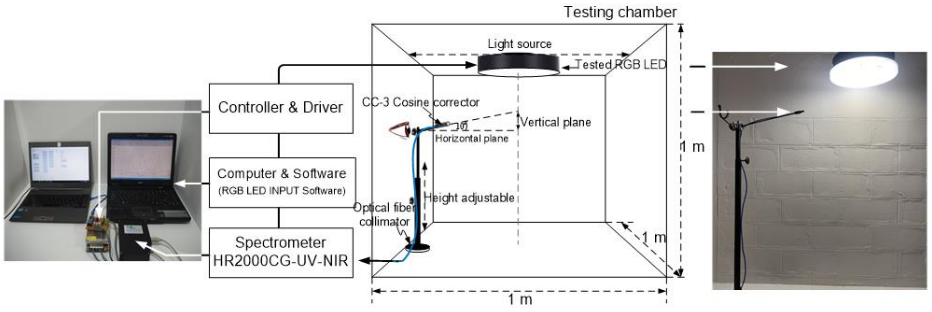
2.2. Design of a daylight mimicking and evaluation

The experiment was setup in a manner that would permit the validation of artificial lights that could be achieved CCTs, chromaticity x-y co-ordinates, and other parameters in conformance to CIE recommendations. The schematic of the measurement system for RGB-LEDs is represented in Figure 2. The tested LEDs were screened and selected from a number of various commercially available RGB-LEDs that could be obtained with the setup devices. It also schematized the algorithm diagram to input of the assigned RGB encoding for exposure of each light color. RGB-LEDs were controlled and driven by three electrical current sources with specific characteristics of RGB for LED-A and LED-B at a final wattage of 30 W, as shown in Table 2. LED-A consists of 100 bits of lower power LED (0.3 W), whereas LED-B consists of 3 bits of high-power LED (10 W). A commercial 24-W RGB LED lamp (c-LED) was used to compare their spectral optic efficiencies.

To evaluate the arbitrary light quality of LEDs, optical power proportions of blue, green, and red LEDs were encoded to targeted CCTs via simulations and optimizations using ColorCalculator software (version 7.77, Osram, USA). The empirical formula of optical powers versus currents was later derived. The LED setups were assigned to the CCTs based on the Plankian locus and the standard locus of the artificial lights (ANSI, 2,000) at 3,000-10,000 K, using RGB-LED input software as represented in Figure 2(a). During the experiment, light was generated above a CC3-cosine corrector at an intensity level of 500-1,000 lx in a 1 m^3 white box as shown in Figure 2(b). The light emitted was collected using a 500 mm integrated sphere probe, transferred through an optical fiber collimator, and recorded by a high-resolution spectrometer (Ocean Optics, model HR2000CG-UV-NIR, USA). The spectrum was collected by OOIBase32^{TM} software (version 2.0.1.3, Ocean Optics, USA) and subjected to analyse for photometric and radiometric parameters by ColorCalculator Software (version 7.77, Osram, USA).



(a)



(b)

Figure 2. Two LED setups used for daylight-mimicking system (a) LED-encoding controller system and (b) layout of the measurement platform

Table 2. Characteristics and lighting profiles of the LED setups

Parameters		LED-A	LED-B	c-LED
Power (W)		0.3	10	24
Forward voltage (V)	Red	2.0-2.2	6.0-8.0	N/A
	Green	3.0-3.2	9.0-11.0	N/A
	Blue	3.0-3.2	9.0-11.0	N/A
Working current (mA)	Red	20	1200	N/A
	Green	20	1050	N/A
	Blue	20	1050	N/A
Dominate wavelength (nm)	Red	620-625	620-630	590-600
	Green	520-525	520-530	520-535
	Blue	465-470	460-470	450-460
Luminous intensity (mcd)	Red	700-1,000	28,6447-38,197	N/A
	Green	2,200-3,300	76,394-85,944	N/A
	Blue	1,100-1,500	9,549-19,099	N/A
Power supply voltage (V_{DD})		+3.5~+5.5 V	+6.0~+12.0 V	+6.0~+12.0 V
Logic input voltage (V_I)		-0.5~VDD+0.5 V	-0.5~VDD+0.5 V	-0.5~VDD+0.5 V
Operation junction temperature (T_{opt})		-40~+85 ºC	-25~+100 ºC	-20~+100 ºC
Storage temperature range (T_{stg})		-55~+150 ºC	-40~+120 ºC	-50~+120 ºC
Beam Angle (θ)		120º	120º	120º

2.3. Evaluation of the arbitrary light quality of the RGB-LED

2.3.1. Mimicking of the tropical daylight

The daylight mimicking was simulated according to the optical daylight readings collected during a clear-sky day in the summer (mid-May) and in the winter (mid-November). Daytime lighting variable were calculated hourly (06:00 to 18:00) using ColorCalculator software (version 7.77, Osram, USA). RGB codes were generated according to the specific points of the x-y co-ordinates. After that, the obtained RGB codes were assigned at various specific times to the RGB-LED input software in the AutoRun mode as shown in Figure 2. The program was applied to the LED-A and LED-B setups, and the emitting lights were collected and analysed in the same way as described in the section 2.2.

2.3.2. Analysis of arbitrary light quality

Various attained CCTs of mimicked daylights of LED-A and LED-B setups were determined by carrying out spectral optimizations [26]. Spectra of RGB-LEDs under different combinations of I_R, I_G, and I_B according to the recalculated to CCTs were later obtained. The comparison between the arbitrary CCT of RGB-LEDs (CCT_1) and the attained CCT of light (CCT_0) is performed with the CCT deviation (δ_{CCT}) between these two CCTs defined by (7). The latter, the Duv values of the LED of the LED-A and LED-B by the mimicking of the summer and winter daylights were also compared using the deviation of Duv (δ_{Duv}) as showed in (8).

$$\delta_{CCT} = \frac{|CCT_0\text{-}CCT_1|}{CCT_0} \times 100\% \quad (7)$$

$$\delta_{Duv} = \frac{|Duv_0\text{-}Duv_1|}{Duv_0} \times 100\% \quad (8)$$

Furthermore, circadian parameters of the light samples such as mELR, mDER and mEDI were also be analyzed using the CIE S 026 α-opic Toolbox-V1.049a-2020/11/16 [27], [28].

2.4. Statistical analysis

The paired sample t-test was used to analyse the significant differences between the mimicked daylight from LED-A and LED-B setups for arbitrary CCT and Duv values. The analysis of variances (ANOVA) was conducted to test for the differences of mimicked light from LED-A and LED-B setups compared to the natural daylight in summer and winter. The social statistical packaging program (SPSS, version 22.0, USA) was used to run the tests at the confident level of 95%.

3. RESULTS AND DISCUSSION

3.1. Qualitative analysis of light source

3.1.1. Spectral power distribution

The entire daytime cycle of the sun was measured on clear-sky days in Thailand during 10-15 May 2020 (Thailand's hot season/summer) and 10-15 November 2020 (Thailand's dry or cool season/winter) as samples. On a summer day, sunrise occurred at 05:37 and sunset occurred at 18:30 therefore measurements were recorded from 05:30 until 19:00. On a winter day, sunrise occurred at 06:11 and sunset occurred at 17:30 therefore measurements were recorded from 06:00 until to 18:00. Because the spectrum of daylight is closely related to the daylight incident angle, which is symmetrical in the forenoon and afternoon, parameters of daylight were also analyzed for CCT and x-y co-ordinate values.

Figure 3 shows the differences in the SPD between 300 and 900 nm during these two clear-sky days. The SPD patterns were directly related to levels of light intensity on the summer day as shown in Figures 3(a) and 3(b) and the winter day as shown in Figures 3(c) and 3(d). The peak of the SPD could increase significantly, affected by increases in the angle of the sun on the area of observation. Therefore, blue sunlight or a mixture of golden light in the early morning hours or during the evening sunset is often observed, which is called “golden hour” in the morning and “blue hour” at noon [29].

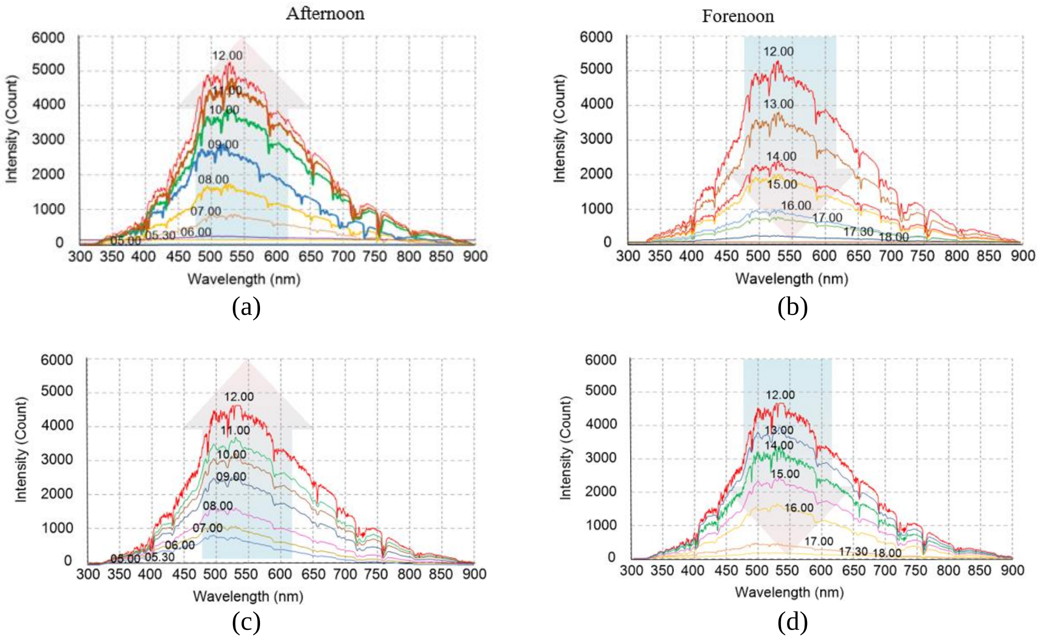


Figure 3. The intensity of circadian light in a tropical zone in summer (a) from sunsrise to noon, (b) from forenoon to sunset and winter, (c) from sunsrise to noon, and (d) from forenoon to sunset. This study was conducted at Kosum Phisai District, Maha Sarakham Province, Thailand

3.1.2. The chromaticity coordinates of sunlight

The precise color of a light source, independent of its luminance, can be derived from tristimulus values [30]. The two-dimensional plane diagram, shown in Figure 4(a), is the CIE 1931 (x, y) chromaticity diagram. The chromaticity coordinates can be used to display color mixing of light sources according to Grassmann’s law [31]. In this study, the chromaticity co-ordinates of dynamic daylight during clear-sky days in summer and winter are shown in Figure 4(a). The vertical narrow line compares two different lightings that represents CCTs level at the specified sun incident angle, with varied distortion effect due to atmospheric humidity. This narrow CCT scale line is used to derive the CCT for the daylong and year-round models. The chromaticity coordinates were changed from low CCT to high CCT along the Planckian locus in the forenoon, and then returned back in the afternoon. Obviously, dynamic daylight CCT on the summer day was different from those observed in winter. The CCT of summer daylight ranged 5,000-6,000 K, which was narrower than the winter range (5,000-7,000 K). Moreover, the CCT of each season was deliberated in different directions.

Furthermore, Duv values were varied for summer (0.015-0.036) and winter (0.033-0.037). A positive deviation from the Planckian locus is possibly caused by the scattering in the atmosphere. Because of the study location’s latitude and the solar longitude during 10-15 May and 10-15 November 2020, the vertical incidence of daylight times were averaged at 12 h 53 min (05:37-18:30) in the summer and 11 h 22 min (06:11-17:33) in the winter. The solar incident angles of daylight in both seasons were also reported in three major solar angle including nautical twilight (solar planar<0 degree), civil twilight (solar planar 0-6 degrees) and noon (center point of maximum daylight intensity). Therefore, nautical twilight and civil twilight are presented twice a day in the early morning until sunrise and again in the evening during sunset. During this study, civil twilights on a summer day were observed during the morning (05:14-05:37) and evening (18:30-18:53). Civil twilights on a winter day were observed during the morning (05:48-06:11) and evening (17:33-17:56). This observation confirmed the well-known phenomena that daytime is shorter in the winter than in the summer for the northern hemisphere. This is due to the typical seasonal changes caused by changes in solar angles which affect the SPD irradiation of sunlight and cause different patterns of light at various times. Variations also occur based on location, effected by the earth's latitude and changes in atmospheric quality. Generally, in the morning and at dusk, the SPD is more concentrated with long wavelengths, while the spectral power is more concentrated in short wavelengths at noon. In this study, the experiment was done on summer and winter days in Thailand, where there is about 35-degree difference in 6 months duty cycle of solar angle on irradiation: 90 degrees shortly after noon (12:04) in the summer and 55 degrees just before noon (11:52) in the winter.

As mentioned above, the two major parameters of light, continuous spectrum distribution and dynamic CCTs, change daily throughout the year, between 5,200 and 7,000 K depending on the time of day and the month as shown in Figure 4(b). In the summer, the CCT values of the typical points started with 10 lx of 2,700 K at 05:30 a.m., then deliberated to the highest intensity of 100,000 lx to 5,700 K at mid-day, and dynamically returned to 20 lx of 2,780 K at 18:00 p.m. However, in the winter, the CCT values of the daylight was quite different: starting at 10 lx of 5,300 K in the early morning, reaching maximum intensity at 100,000 lx of 7,000 K mid-day, and dimming at sunset to 10 lx of 5,300 K.

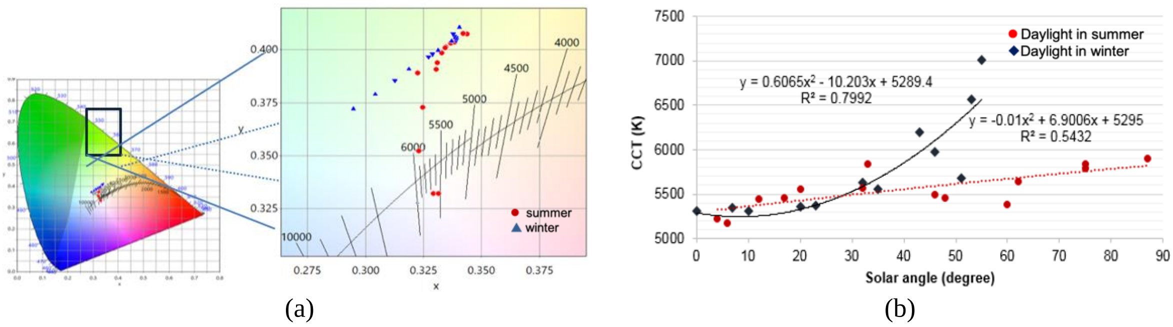


Figure 4. The chromaticity diagrams of the daylights (a) in summer and winter and (b) sunlight color temperature as a function based on the distribution of sun elevation angle on clear-sky days on summer and winter days

Figure 4 shows the daylight characteristic were different characteristics including deliberating the daily CCT values and the dynamic changes during throughout a day in different direction as showed on the chromaticity diagram. This is mainly caused by the orientation of the earth's annual cycle around the sun. Moreover, depending on the season, fluctuations in temperature affect light color during the course of the day, which is additionally affected by atmospheric conditions, such as humidity, dust particles, fog, smoke, and pollution. Indeed, during some summer periods in Thailand, storms frequently formed producing a high content of dust particles in the air; consequently, the SPD measurements likely fluctuated during stormy periods [32]. In contrast, during the early winter in Thailand, storms may also occur with some rainfall, but these conditions are generally followed by cold air masses that produce drier atmosphere conditions. Because the sky is often much clearer in the winter than in the summer, the purity of the daylight in the winter was somewhat higher than in the summer, thereby causing the CCTs of the daylight to be higher during the winter [33].

3.2. The radiometric and photometric properties of the artificial lighting

It is important to be aware that the color of white light emitted also affects the circadian cycle. In this work, two artificial lighting systems were assembled: LED-A and LED-B setups. Bulbs were analyzed to determine SPDs at luminous intensities between 1,000-1,200 counts for both systems. Figure 5 shows the SPD of the artificial light from two setups at CCT ranges of both cool white as shown in Figures 5(a) and 5(b) and warm white as shown Figures 5(c) and 5(d), with the cutting point of 5,000 K. The SPD of LED-A setup exhibited three peak light spectra: blue-light spectra at 465 nm, green at 518 nm, and red at 635 nm. LED-B setup attained three similar peak light spectra: blue-light spectra at 455 nm, green at

522 nm, and red at 626 nm. Hence, the λ_{max} differences between the tested lamps were 10 nm for blue, 4 nm for green, and 9 nm for red. Additionally, the c-LED was given those peak spectra at 468 nm for blue, 522 nm for green, and 632 nm for red light. Interestingly, the CCT light transformation in LED-A and LED-B had different patterns. LED-A had dynamic changes in peaks of I_B, I_G and I_R intensities, while LED-B had a different dynamic adjustment to the attained CCTs with a fixed value of I_R, but varied values for I_B and I_G.

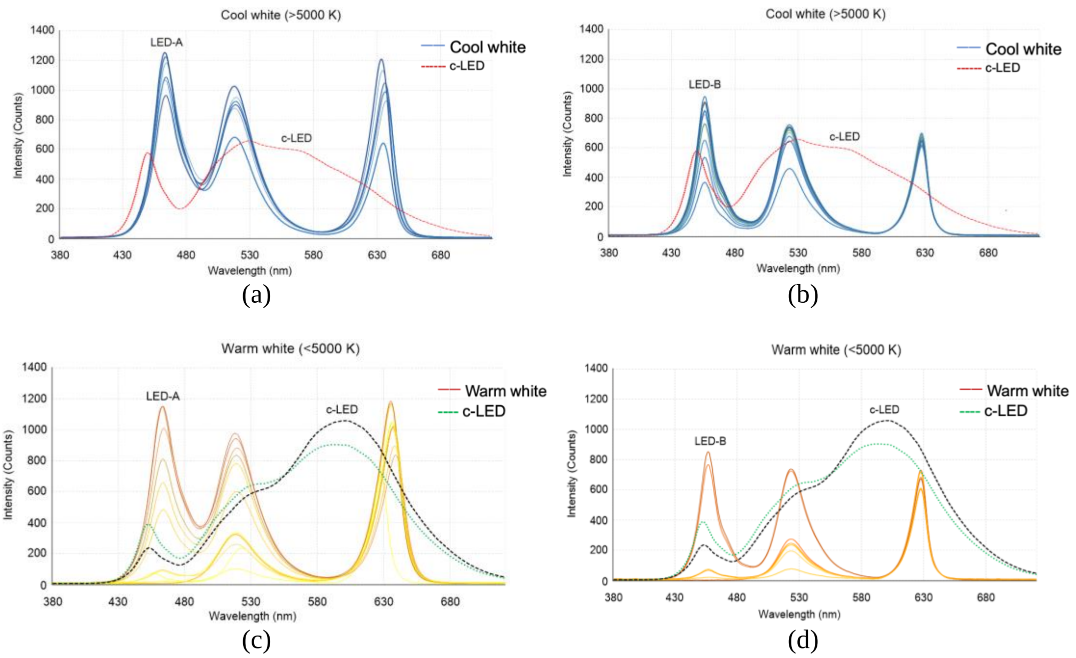


Figure 5. The spectral power distribution of lighting from the two setups compared with commercial LED (c-LED). The cool white lighting samples (blue lines) comprised (a) LED-A and (b) LED-B lighting. The warm white lighting samples (orange lines) comprised (c) LED-A and (d) LED-B

These factors explain the differences in the arbitrary CCTs, light color shading, the precision on the Plankian locus, LER and LE, as shown in Figure 6. The MacAdam ellipses showed a deviation in the artificial light compared to the D65 standard as found in Figures 6(a) and 6(b). The longer distance of the reproduced CCT points on the chromatogram indicates the lamp's inefficiency, whereas the nearest of the CCT point on the Plankian locus and ANSI standard line of the artificial lamp indicates more efficiency. Comparing the two setups, the LED-A showed more consistency regarding the locus alignment in both cool white and warm white CCTs than those observed in the LED-B. However, both setups fluctuated and shifted noticeably out of the locus at the CCT 6,000 K for LED-A and 5,000 K for LED-B. These limitations might be caused by the lamps' mixture of I_B, I_G and I_R, such that they were unable to emit white color light that attained a higher level of brightness. The LED-A and LED-B setups could also be observed the difference in the light color tone and intensity. Figure 6 also shows the lighting quality parameters at various CCTs produced by LED-A and LED-B (3,000-12,000 K), c-LED (3,000, 3,200, and 3,500 K) and daylight (5,000, 6,000 and 7,000 K) including LER and LE. It was found that LED-A and LED-B setups have similar LER values at various CCTs as shown in Figure 6(c) with the CRI in the range of 43-71 and 60-83, respectively. However, the lights between 9,500-12,000 K, the LER was lower than the lights with lower CCTs. The LER values of this study were similar to previous reports in the range of 260-371 $lm \cdot W_{opt}^{-1}$ [34]–[37]. Additionally, some works found that LER may be decreased with the increase of CCT values [36], [37], while the others found that LER depended steadily on the lighting subtractive components, such as the combination of white light in white RGB LEDs. Similarly, the LE values of LED-A and LED-B setups had the same trends throughout CCTs of 3,000-12,000 K. Compared to the c-LED, LED-A and LED-B possessed lower LER and higher LE than those of c-LED as shown in Figure 6(d). Only LER values can be measured for daylight spectra, which was higher than both LED-A and LED-B. LER values depend on the sensitivity and accuracy of the lighting detector devices, however the LE values depend on the LED property. Therefore, it can be suggested that LED-A and LED-B setups will require higher voltage supply needed to produce the higher

CCTs (especially warm white). In general, LE values for LED light sources varied in a range of 54-100 lm·W^{-1}_{elec}, which depend on the semi-conductor type of the LED [34], [38]. Moreover, it was found that the LE values of LED lamps were higher than those of incandescent, fluorescent, and metal-halide lamps, but lower than those of low-and high-pressure sodium lamps [34], [38].

In this research, both light matrices were used to evaluate the artificial light that relates to range in the circadian system. Figure 6 also shows the relative spectral response curves of both metrics, along with the SPD for the LED white light source at a range of CCT values. This figure highlights potential disagreement between the metrics in the magnitude of impact that changing CCTs might have on circadian stimulus, depending on the location of the violet/blue peak in the source SPD. Given this potential effect, concerns have been raised regarding the impact of LED lighting on circadian rhythms, as stated in a recent USDOE fact sheet [39]. It suggested that chronic disruption of circadian rhythmicity by LED light sources has the potential to yield serious long-term health consequences, although there are no examples in any literature of such circadian disruption arising from the installation of LED public lighting [40].

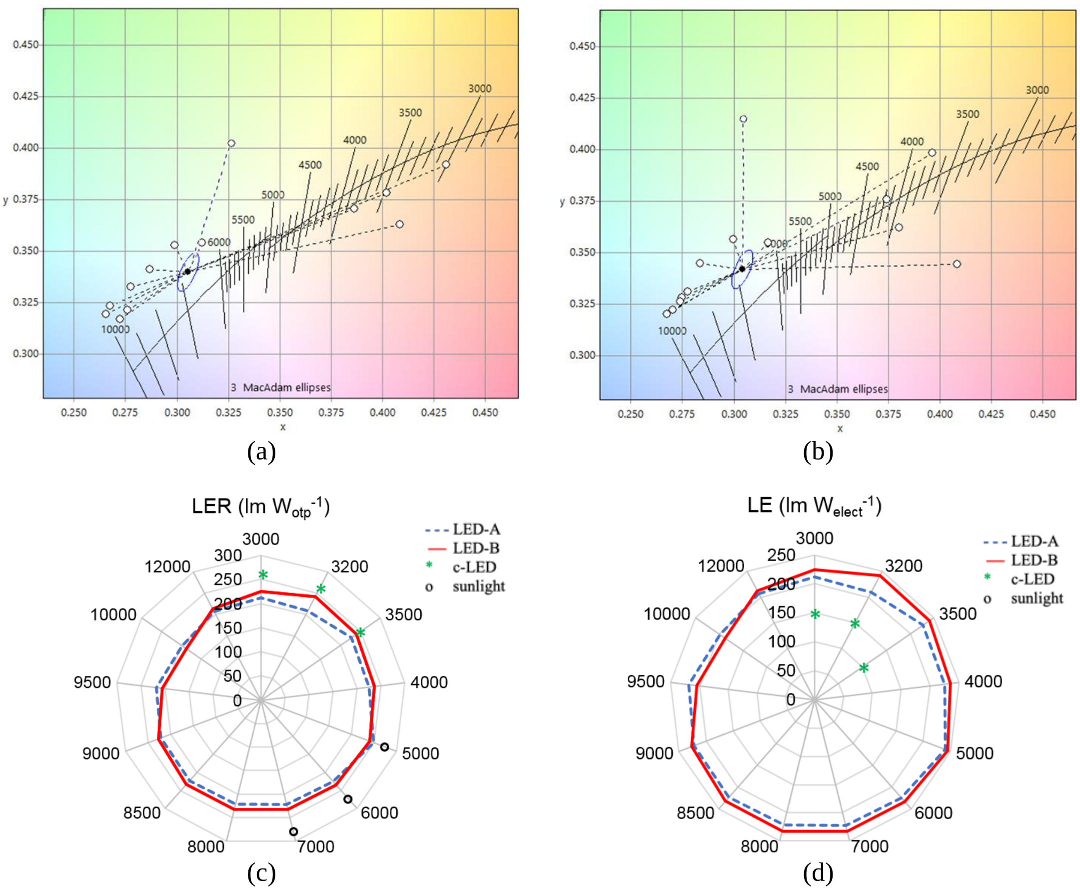
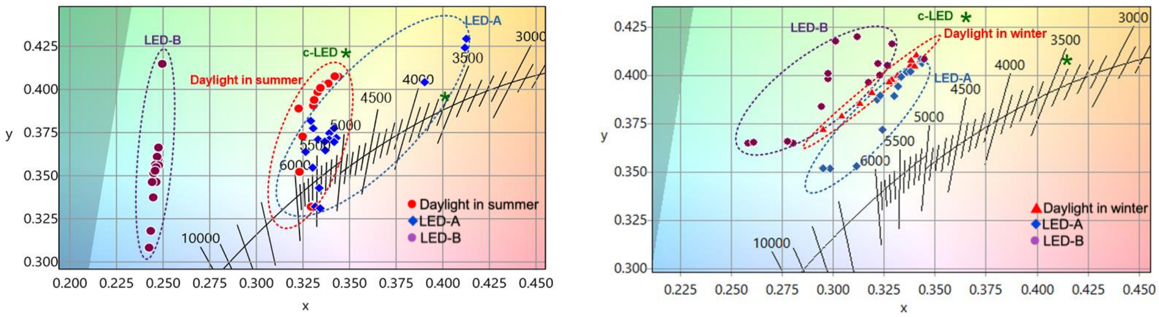


Figure 6. The MacAdam ellipses analysis of deviation in LED-A (a) and LED-B, (b) and lighting quality parameters, (c) luminous efficacy of radiation (LER), and (d) luminous efficiency (LE) of LED-A, LED-B, c-LED and sunlight at various CCTs

3.3. The arbitrary of the artificial lighting on mimicking of daylight

As shown in Figure 7, chromaticity diagrams of RGB-LEDs (LED-A and LED-B) represent co-ordinates of arbitrary CCTs of mimicking daylight during a summer day as shown in Figure 7(a) and a winter day as shown in Figure 7(b). Arbitrary CCTs were somewhat different from assigned CCTs. Comparatively, CCTs of LED-A aligned closer to the Planckian locus and nearer to the assigned CCT regions than LED-B did. The CCT values of LED-A aligned nearly to the circadian daylight in the range 5,000-6,000 K (summer) and 5,000-7,000 K (winter), but just a few points lower than 5,000 K were shifted to the reddish color. For LED-B, the arbitrary CCTs were approximately 2,000 K higher than the assigned CCT values in summer, and about 500 K higher than the assigned CCTs in winter.



(a) (b)

Figure 7. The chromaticity diagrams of the mimicking daylight in (a) summer and (b) winter in Thailand using LED-A and LED-B

Figures 8(a) to 8(d) compares values of CCTs and δ_{CCT} for the two setups in mimicking of daylights (06:00-18:00 in summer and winter). LED-A had an average δ_{CCT} value about 3.75% (in the range of 0.04-10.09%). LED-B had an average δ_{CCT} value about 5.0% (range 0.70–34.42%) which is higher than LED-A significantly (P<0.05). However, no criteria regarding efficiency that established to valuate and select the light source. The deviation of the light reproduced by the LED should be suggested to be account for LED lighting design for daylight mimicking. The daylight with the control system in this study can run according to the assigned scenarios. Furthermore, by the accuracy of the light wavelength and light intensity, the system should be adjusted for the value of the LED color with different backgrounds. This contribution showed that the circadian system could be simulated. Under the assumption that blue light and white light will be able to be used for the circadian program to improve the sleep quality. Figure 8 reports the natural daylight pattern in summer and winter with a comparison of the artificial lighting for LED-A and LED-B setups. The brightness of lighting, indicated by CCTs, is noted by the higher CCTs at mid-day. As shown, the artificial lights produce lower intensity light than the natural light. The artificial light does not need to provide light with the same intensity as circadian daylight because one-tenth of natural light is sufficient for normal human living environments and human activities. Regarding to the comparison of the deviations from the target x-y co-ordinates of the natural daylight in summer and winter, there were significantly differences for the Duv values of the tested LEDs. The LED-A emitted the mimicking lights with the Duv values closer to the target Duv values than those of the LED-B as shown in Figures 8(c) and 8(d). In the mimicking of the summer daylights, the LED-A and LED-B provided the averaged Duv deviations of 61.46% and 153.80% as shown in Figure 8(e), respectively. Similar to the mimicking of the winter daylights, the LED-A and LED-B provided the averaged Duv deviations of 17.36 and 56.84%, respectively. The ideal distance (Duv) to the Plankian locus mainly depends the metameric spectral tuning included the range of the optimising non-metameric spectra [41].

Figure 9 shows melanopic metrices of the tested LED setups on the mimicking of daylights in summer and winter such as mELR, mEDI and mDER values. Indicating to the melanopic potential, the mELR and mEDI for the tested LED setups were calculated to compare with the daylights in summer and winter. The mELR values of the natural daylights in summer and winter were higher than those observed in light samples of the two setups throughout the entire setting time (06:00-18:00). The mELR values of the natural daylights in summer and winter were in the range of 1.54-2.04 and 1.00-1.94 W·lm^{-1}, respectively as shown in Figures 9(a) and 9(b). In summer daylight mimicking, the LED-A gave the emitted light with lower mELR values (average of 1.16 W·lm^{-1}) than those observed in the LED-B (average of 1.52 W·lm^{-1}). This was similar to the daylight mimicking for winter, the LED-A and LED-B gave the mELR values of the emitted light with average values of 1.15 and 1.54 W·lm^{-1}, respectively as shown in Figures 9(a) and 9(b). Obviously, the mELR values have smaller difference during 6-7 h of the day, but they have larger difference at the middle of simulation (10-15 h) as shown in Table 3. The mEDI values of the daylights in summer and winter were in the same trends in accordance to the irradiation of the circadian lighting as previously represented in Figure 2. As compared to the irradiance power of the tested LEDs, there was a difference approximately 10 times between the natural daylight and LED lighting. Therefore, the mEDI values of daylights was in the range of 279-2,546 lx and 86-2,469 lx for summer and winter daylight, respectively as shown in Figures 9(c) and 9(d). Table 3 also shows the averaged mEDI values of emitted light by the LED-A and LED-B were 246 and 250 lx in the summer and 226 and 282 lx in the winter, respectively. Figures 9(e) and 9(f) also show mELR values of the natural daylights, it was found that the mELR of the daylights in summer and winter were higher than 1.00 W·lm^{-1}, except for the daylight at 6 and 18 h of that day.

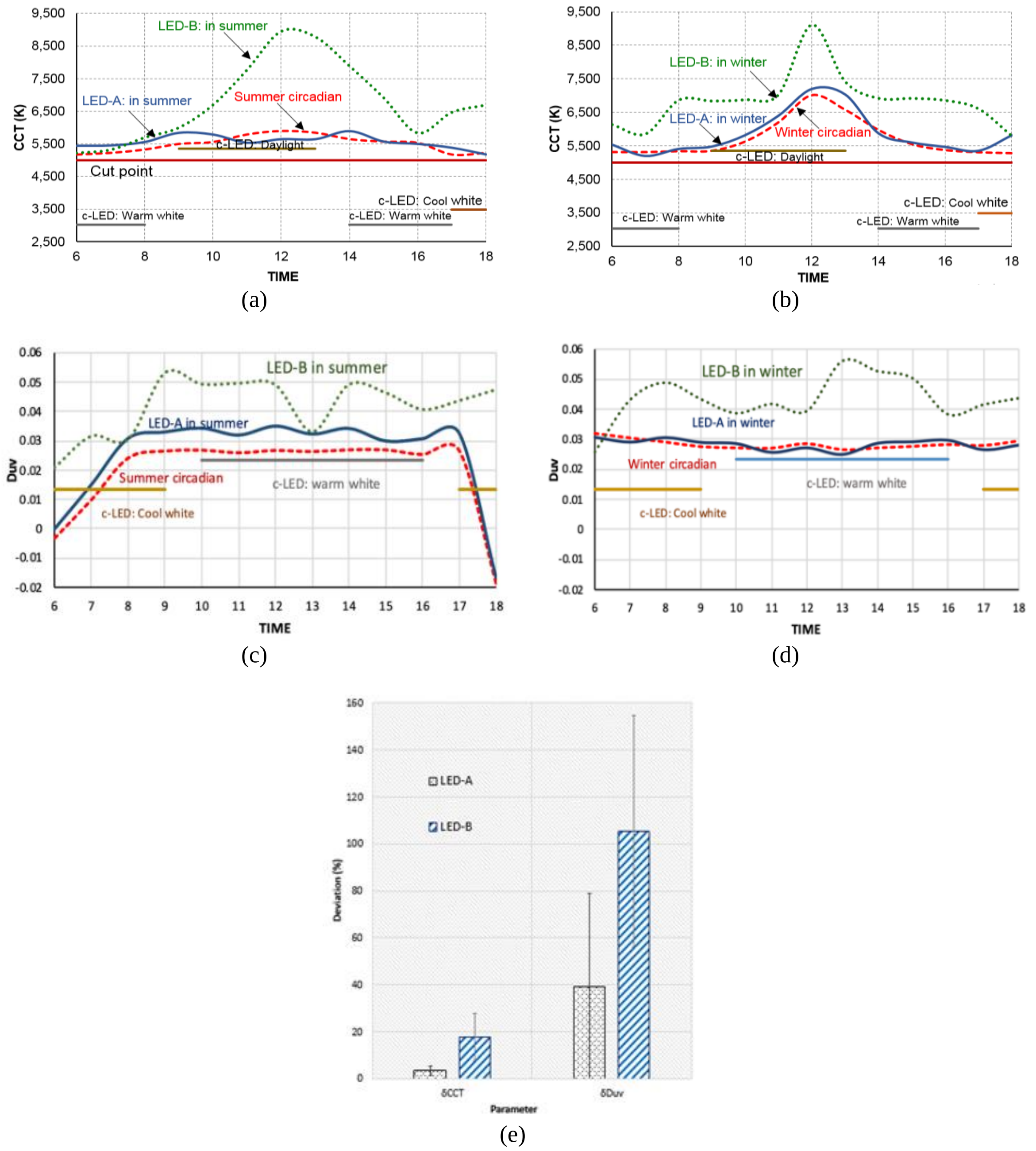


Figure 8. Deviations of CCT of LEDs used in the tropical daylight-mimicking system in (a) summer and (b) winter by the two setups. Deviations of Duv of LEDs used in the tropical daylight-mimicking system in (c) summer and (d) winter by the two setups; (e) The average values of δ_{CCT} and δ_{Duv}

However, the LED-A provided the emitted lights with lower mDER values than those of the LED-B, which had an average mDER of 0.84 and 1.06, respectively as shown in Figures 9(e) and 9(f). The mDER values could be used to indicate the non-visual effect with the standard comparison to the illuminant D65 (6,500 K). Based on the result, it can be said that at the same level of illumination, the LED-A may give a light with lower impact on non-visual effect than that of the LED-B as shown in Table 3. The mEDI has been recommended to explore the correlation between α-opic quantities and non-visual responses. The minimal responses of light can be resulted by the mEDI below 4 lx, whereas the strongly responses of light for melatonin suppression needs the light with the mEDI over 300 lx [8], [42]. The mDER obtained from the tested LED setups was similar in the coverage trends. This supports the previous finding that the mDER for daylight on a clear sky day is greater than the mDER of white LED lighting [8]. Therefore, the LEDs for producing melanopic light by combination of CCTs and luminous flux with tunable M/P ratios may given more efficient [8]. It is found that mDER values of LED-A and LED-B are lower than those of the natural daylight in summer and winter. This indicates that the tested LED setups gave a lower M/P ratio than the natural daylights. The LED-B provided the emitted lights with higher M/P ratios than those of the LED-A along with the assigned scenarios. The light with high M/P ratio tends to be similar to daylight, thus it could be recommended for the daytime indoor. On the contrary, the light with low M/P ratio could be used to minimize melanopic light exposures such as night lighting [8]. From the analysis of malanopic effect of the two setups, LED-A setup gave lower photobiological potential than LED-B setup at the same illumination. This indicated that LED-A setup could give a higher illumination than LED-B setup. Therefore, LED-A setup is appropriate to be used for indoor lighting, while LED-B setup is appropriate to be used for outdoor lighting.

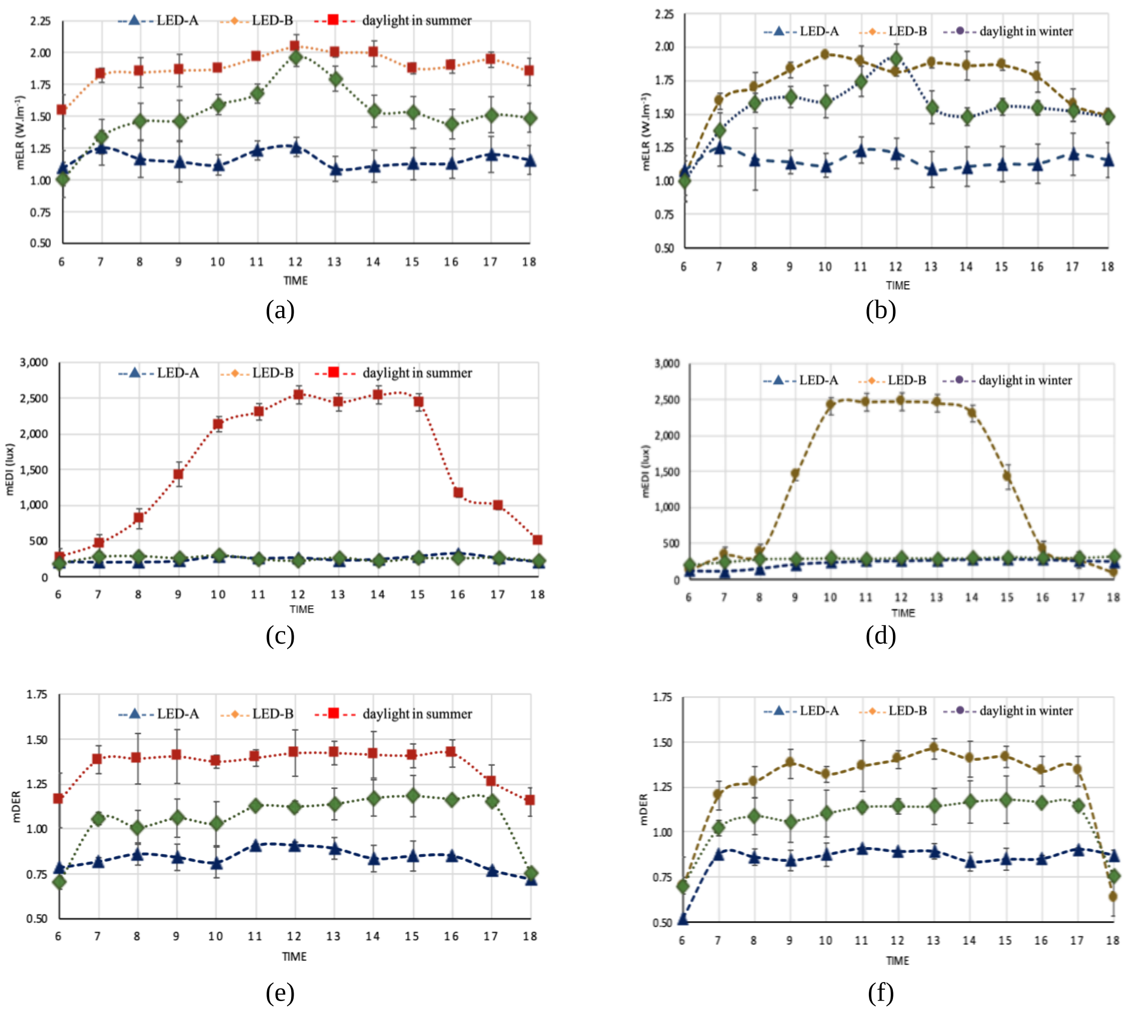


Figure 9. The melanopic efficacy of luminous radiation (mELR) for the mimicking lighting for (a) summer and (b) winter daylights. The equivalent daylight (D65) illuminance (mEDI) for the mimicking lighting for (c) summer and (d) winter daylights. The daylight efficacy ratio (mDER) for the mimicking lighting for (e) summer and (f) winter daylights

Lok *et al.* [43] reported to the impact of four lighting conditions of the same photopic illuminance (100 lx) and similar CCT (~4,000 K) but differed in the spectral composition, except dim light which was 10 lx. The strength of mELR as well as the mEDI for each of the lighting conditions: dim (mELR= 0.770 W·lm^{-1}, mEDI=2.25 lx), fluorescent (mELR=0.770 W·lm^{-1}, mEDI=56.2 lx), broad-spectrum LED (mELR=1.06 W·lm^{-1}, mEDI=80.6 lx), and standard LED (mELR=0.993 W·lm^{-1}, mEDI=73.2 lx). It could be suggested that daytime exposure to white light with high melanopic efficacy has the potential to improve daytime cognitive function and that such improvements are likely to be direct rather than a consequence of light-induced changes in alertness [44]. Additionally, Zandi *et al.* [41] revealed that using of multi-channel

LEDs does not have significant benefit for non-visual purposes, but it possibly to make an advantage of varying visual matrices with narrow down the metamer contrast that would be increased intolerance by temperature fluctuation of LEDs or measurement inaccuracies. Noor *et al.* [44] revealed that the latest standard show that EDI can be the most appropriate metrology to investigate the non-visual effects of light. However, M/P is one of the proposed measures that widely used to consider both the photopic and melanopic effects of indoor lighting. Therefore, in this work, the new CIE non-visual (melanopic) standards included mELR, mEDI and mDER were taken to be account for screening and selection of LEDs to be used in a tropical daylight mimicking. So far, mEDI become more potential to be used in evaluation of circadian-effective illumination such as using in a standard observer methodology for development of standard observer watts [45]. The standard recommended to assess the luminaries need to reach the circadian stimulus of 0.3, which is the illumination of 292 lux and EDI=194 of 5,000 K LED. This is an example for estimation of the circadian-lighting measures [45]. Our results could be showed the CIE-standard for melanopic performance implemented to evaluate the candidate RGB-LED to be used for further purposes such as development for a circadian lighting system, combination of white-LED with RGB-LED to improve lighting co-ordinates. Importantly, the validation process of LEDs with the standard melanopic performance could be a benefit for user by overviewing of the RGB-LED producing light quality and their limitations entire the course of model used, thus making for solution to archive the goal.

Table 3. Comparisons of averages and ranges (min-max) values of mELR, mEDI and mDER of daylight, LED-A and LED-B in summer and winter

Mimicking season	Summer			Winter		
Light source	LED-A	LED-B	Daylight	LED-A	LED-B	Daylight
mELR ($W \cdot lm^{-1}$)	1.16	1.52	1.88	1.15	1.54	1.71
	(1.09-1.26)	(1.00-1.97)	(1.54-2.04)	(1.08-1.25)	(1.00-1.92)	(1.00-1.94)
mEDI (lx)	246	250	1,544	226	282	1,273
	(202-327)	(188-299)	(279 -2,546)	(112-280)	(198-317)	(86-2,469)
mDER	0.84	1.05	1.35	0.84	1.06	1.25
	(0.72-0.91)	(0.70-1.18)	(1.15-1.42)	(0.52-0.91)	(0.70-1.18)	(0.63-1.46)

4. CONCLUSION

This work focused on investigation of essential information needed to design a dynamic artificial lighting system that could effectively support humankind's daytime needs, year-round (summer and winter) based on the biorhythms promoted by circadian light. The goal was to design an artificial lighting system that best matches the natural daylight characteristics found in a tropical zone (in this case, Thailand). The study found that the wavelengths and intensity of daylight varies a lot throughout the hours of a day, and vary according to the season. The SPD for each time of the day varies most significantly according to the season. During the summer, daylight spectra possess some red shift, which contrast to wintertime patterns. Therefore, different chromaticity layouts of the daily CCTs allocated on the Planckian locus could be observed. With regards to RGB-LEDs used to mimic circadian light, the LED type should be taken into account for a validation process. In this study, two LED setups (LED-A and LED-B) were used to create an artificial LED system that could produce various CCTs within the Planckian locus (3,000-10,000 K) based on the radiometric and photometric analysis. Finally, LED-A and LED-B setups were assigned the CCTs according to the circadian spectrum from the first part by the RGB-LED input software. Considering the circadian efficiency of the light source, LED-A setup is recommended to be used indoors to mimic circadian lighting. Based on calculated values of CCTs, Duv deviations and the malanopic standards. It was found that LED-A setup was more compromising with the circadian point on the chromaticity diagram than LED-B setup. While characteristics from c-LED did not give any satisfactory outcome due to fixed light outputs. It is possible to enhance LED-A setup by increasing the white light and more channels of RGB LEDs to match circadian light more closely through dynamic lighting control, which would make it more appropriate and easier to use in real situations with varying light intensities. In the selection of general commercial RGB-LEDs to be used effectively depends on the purpose of usage, CRI, the ability of lighting reproduction range of interest (CCT, x-y co-ordinates, and Duv) and the circadian impacts (mELR, mEDI, and mDER).

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