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Development Method of High CRI LED Lighting Reflecting the Spectral Ratio Characteristics of Natural Light by Wavelength Band

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Abstract

Although natural light is the standard reference for color rendering evaluation, limited efforts have been made to develop a lighting system that achieves high color rendering while replicating the spectral characteristics of natural light. This paper proposes a method for developing LED lighting that mimics the spectral ratio characteristics of natural light and achieves high color rendering. Based on the analysis of measured natural light spectra, spectral ratio characteristics are derived according to changes in color temperature. Simulations are conducted by adding light sources with specific peak wavelengths (405 nm, 630 nm) to commercial LED lighting. Based on the simulation results, a development approach for natural light LED lighting with high color rendering is proposed. Experimental results demonstrate that a color rendering index (CRI) of 90 or higher (including R9 and R12 ≥ 80) can be achieved for lighting systems with baseline CRI values of 80, 85, and 90.

Keywords: natural light LED realizing high CRI, color rendering index (CRI), spectral ratio of natural light, analysis of characteristics of natural light, spectral power distribution (SPD)

1. Introduction

Lighting technology continues to develop to achieve light similar to natural light [1]. Efforts have continued to reproduce the characteristics of natural light, such as simulating wavelength characteristics using technology that provides illuminance and color temperature changes [2-3]. Recently, technology that achieves high color rendering performance, similar to natural light, has been emphasized [4]. Color rendering performance refers to the accuracy with which the original color of an object can be reproduced when illuminated by a light source [5]. The most representative criterion of color expression performance is the color rendering index (CRI) [5-6]. CRI indicates how accurately the lighting expresses the tested colors from TCS1 to TCS8 compared to the reference light source [7-8].

Historically, the CRI was defined as Ra for eight colors with medium saturation, which has a limitation in evaluating highly saturated colors [5]. Later, it was improved to enable the evaluation of diverse colors with high saturation by subdividing it into Ri (i = 1–14) [5]. Beyond CRI, improved color rendering performance indices such as the color quality scale (CQS) and TM-30 have been introduced, and their use is increasing [9]. However, most commercial LED lighting products present CRI as the standard for color rendering performance. Recently, they have also been labeled with CRI indices such as R9 and R12, which correspond to red and blue, respectively. Natural light is considered the best for representing the natural color of objects, as it includes the full spectrum of visible light (380–780 nm), and is used as a reference light source when calculating CRI [10-11]. On the other hand, commonly used LED lighting has the disadvantage of low CRI due to uneven spectral distribution or a narrow spectral band [12-13]. Research and development efforts in the lighting field continue to address this drawback.

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High-color-rendering light sources that mimic the spectrum of natural light have been introduced, and technologies have been developed to improve CRI by configuring and controlling multiple LED channels. Zhao et al. [14] developed quantum dot LEDs that simulate the solar spectrum for intelligent lighting applications. Seoul Semiconductor [15] developed a light source that provides a CRI of 95 (R9 > 85) or higher across correlated color temperatures (CCTs) of 2,700–6,500 K by simulating the spectral power distribution (SPD) of natural light. Ji et al. [16] analyzed the color-rendering characteristics of natural light at sunrise, sunset, and daytime and sought to replicate them by combining and controlling multi-channel LED light sources. Dai et al. [17] provided light with a CRI of 85 or higher, approaching 90, under four CCT conditions within the range of 4,000–13,000 K using a color-mixing method with an RGBW LED cluster.

Lee et al. [18] proposed a method to improve the CRI of R9 and R12 under specific color-temperature conditions using spectral simulation. Additionally, attempts have been made to derive the control zone for optimal CRI by adjusting the intensity of a specific wavelength band under the spectral conditions of multi-channel LED lighting [19]. Through these technological efforts, LED lighting with a CRI of 80 or higher has gained popularity, and high-color-rendering lighting with a CRI of 90 or higher is also being launched [16, 20]. However, in recent years, in addition to the general CRI of Ra, which has limitations in evaluating highly saturated colors [21-22], the use of special CRIs (R9–R15), which include additional color samples (TCS9–TCS15), has been increasingly considered [23-25]. Specifically, in applications requiring high color fidelity, information on special CRI values, such as R9 (red) and R12 (blue), is also provided, and high-quality LED designs have been proposed using advanced phosphors and multi-chip configurations [26-28].

Therefore, lighting that simulates natural light must reflect the wavelength characteristics of natural light as much as possible to achieve high color rendering performance and present CRI performance, including R9 and R12. However, there are currently very few studies on lighting technology that improve CRI based on the wavelength characteristics of natural light, and color rendering performance has not been fully considered, as special CRIs have not been widely adopted. This paper proposes a development plan for natural light LED lighting that realizes high color rendering by analyzing and applying the spectral ratio characteristics of natural light. The overall structure of this study is as follows, and Table 1 outlines the main processes.

Table 1 Outlines the main processes

(1) Analysis of measured natural light	• Spectral extraction of measured natural light for each season • Analysis of wavelength ratio characteristics under various CCT conditions of natural light
(2) Analysis of commercial lighting	• Selection of 3 types of commercial lighting • Spectroscopic measurements and analysis of wavelength ratio characteristics of experimental lighting
(3) Spectroscopic-based simulation	• Simulation of SPD combination of natural and artificial light • Experimental application of virtual light sources with peak wavelengths of 405/630 nm
(4) Development of high CRI LED lighting	• Improved SDR application through the addition and control of a 405 nm and 630 nm peak light source • Deriving a plan to improve the CRI of general lighting by reflecting natural light SDR
(5) Experiments and Evaluation	• Performance evaluation of three types of experimental lighting that meet CRI $\geq$ 90 and R9, R12 $\geq$ 80

The organization of this paper is as follows. Section 2 analyzes optical characteristics, such as the CRI and spectral ratio, based on the SPD of measured natural light. Section 3 presents a development plan for high-color-rendering LED lighting that aligns with the spectral characteristics of natural light. Section 4 discusses the experimental results that demonstrate the feasibility of achieving high color-rendering performance using the proposed method. Finally, Section 5 presents conclusions and outlines future research directions.

2. Analysis of Characteristics of Natural Light

To develop high-color-rendering LED lighting based on the spectrum of natural light, the characteristics of actual natural light were first analyzed. For this analysis, natural light data collected from 2017 to the present using a spectroradiometer (CAS 140CT, Instrument Systems, Germany, Smart Natural Space Research Centre) at a location with a latitude of 36.85 and a longitude of 127.14 were used. To measure natural light, a temperature-controlled enclosure and a solar tracker were installed on the rooftop of a 10-story building. A database of natural light characteristics was constructed by measuring natural light continuously for 24 hours a day on all days except those with heavy rain or snow. One bright day from each season was then selected from the database. For each hour, the visible light spectrum (380–780 nm) was extracted, and light characteristics such as CCT and CRI were calculated from this data. Figs. 1 and 2 show the results of extracting and analyzing natural light characteristics for each season.

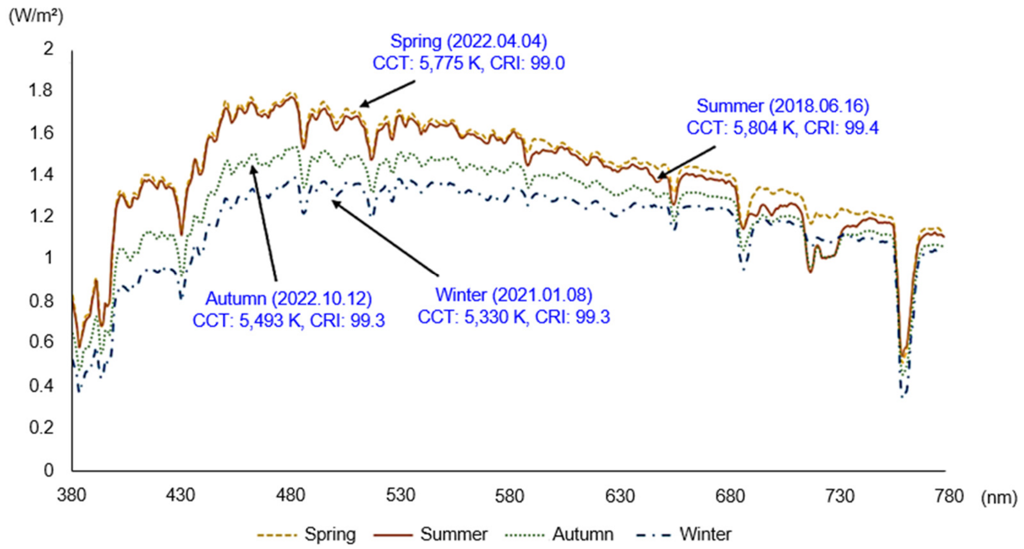


Fig. 1 Example of actual SPD: noon on the selected days for each season

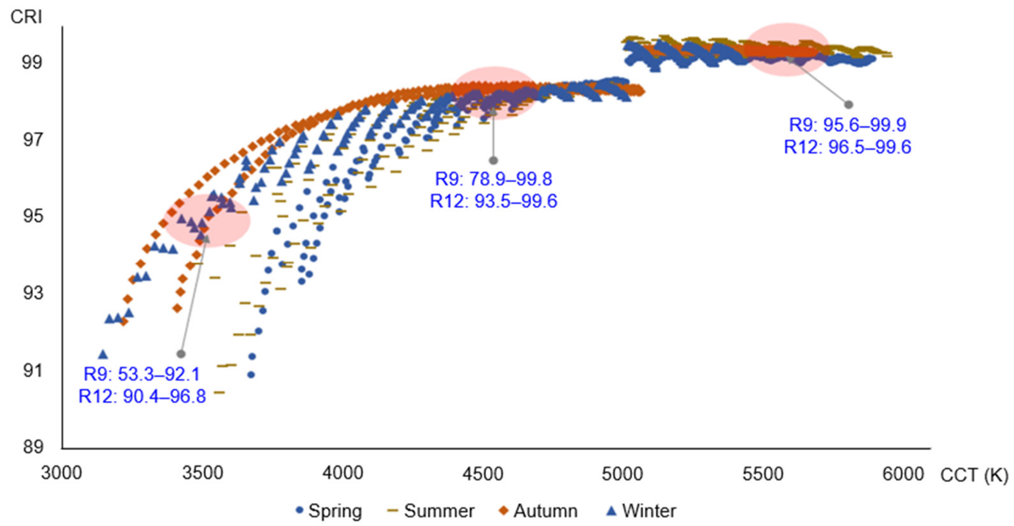


Fig. 2 Measurement results of optical characteristics of natural light: Distribution of CCT, CRI

As shown in Fig. 1, the SPD of natural light tends to be low near certain wavelengths (380 nm and 750 nm), but is generally evenly distributed across the visible wavelength range (380–780 nm). The SPD patterns were similar across seasons, although relatively higher in spring and lower in winter. The color temperature at noon varied by season, with high values of 5,775 K and 5,840 K in spring and summer, respectively, and low values of 5,493 K and 5,330 K in fall and winter. The CRI was consistently 99 in all cases, indicating similarly high values across the range of color temperature conditions.

As shown in Fig. 2, the distribution characteristics of CCT and CRI for all time zones on the selected dates by season are shown. The CRI values were above 99 in the 5,000 K to 6,000 K range, 97 to 98 in the 4,000 K to 5,000 K range, and 91 to 97 in the 3,000 K to 4,000 K range. Both R9 and R12 were above 95 in the 5,000 K to 6,000 K range, but values below 90 were also observed in the remaining ranges. In particular, R9 exhibited notably low values of 78.9% and 53.3%. Subsequently, the spectral ratio characteristics of natural light under color temperature conditions of 3,500 K, 4,500 K, and 5,500 K were derived for selected days in fall, and the results are shown in Fig. 3.

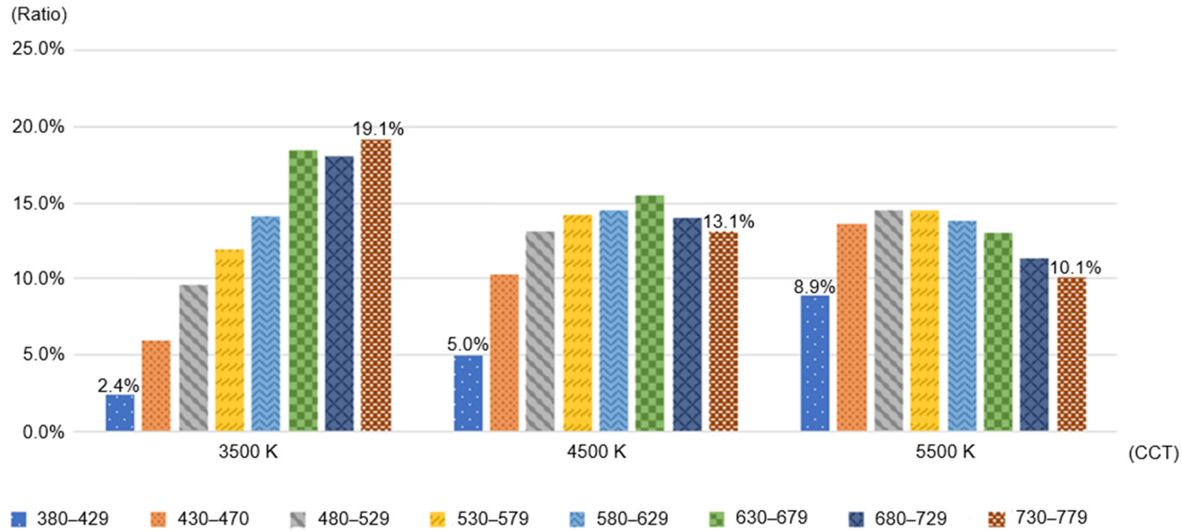


Fig. 3 SPD ratio characteristics by wavelength band under natural light color temperature conditions

As shown in Fig. 3, the spectral ratio of natural light varied for each color temperature condition. At a color temperature of 3,500 K, it was the highest at 2.4% in the 380–429 nm band and 19.1% in the 730–779 nm band. Even under color temperature conditions of 4,000 K and 5,000 K, the spectral ratio for each wavelength band showed different levels. Overall spectral ratios were evenly distributed under all color temperature conditions. Therefore, when developing LED lighting based on natural light characteristics, high color rendering would be possible if the spectral ratio for each wavelength band is maintained evenly under various color temperature conditions.

3. High Color Rendering LED Lighting Based on the Spectral Characteristics of Natural Light

In this study, a multi-channel LED lighting system is proposed that achieves high color rendering by providing spectral characteristics similar to those of natural light. First, three types of commercial LEDs (Light1–Light3) with different CRI characteristics were selected as experimental lighting. Assuming regular LED, high-color-rendering LED, and ultra-high-color-rendering LED, lightings with CRI of 85, 90, and 95, respectively, were selected under a color temperature condition of 5,500 K. Regular LED and ultra-high-color-rendering LED were manufactured by Company K (Kumkang Enertech, Korea), and high-color-rendering LED was manufactured by Company E (ENTEC Electric & Electronic, Korea), each consisting of two channels. In addition, control functions for each channel were implemented to realize various color temperatures of natural light.

To compare the performance of each lighting, these lights were set to a color temperature of 5,500 K and an illumination intensity of 400 lux, and their optical characteristics were measured according to the control. The optical characteristics of artificial lighting were measured within a lighting cabinet with external light blocked. Artificial lighting was installed on top of the cabinet. A spectroradiometer (CAS 140CT, Instrument Systems, Germany) was positioned 150 cm directly beneath the lighting, in accordance with measurement standards for general lighting set by domestic certification agencies. The optical characteristics were then measured. The optical characteristics of artificial lighting are shown in Table 2.

Table 2 Three types of experimental lighting

Category	LED source	Illuminance (lux)	CCT (K)	CRI (Ra)	R9	R12
Light1	2,700 K, 6,300 K (K-Company)	400	5,503.4	85.3	18.8	65.8
Light2	2,800 K, 8,000 K (E-Company)	400	5,503.3	89.6	71.6	66.7
Light3	2,700 K, 6,500 K (K-Company)	399.9	5,472.6	97.6	93.6	83.0

As shown in Table 2, commercial LED lighting exhibits color rendering performance focused on CRI (Ra). Light1 had a CRI of 85.3, but R9 and R12 showed low values, at 18.8 and 65.8, respectively. Light2 presented a CRI of approximately 89.6, while R9 and R12 were 71.6 and 66.7, respectively. In addition, Light3 had a remarkably high CRI of 97.6, and R9 also showed a high value of over 90. However, R12 was 83.0, which was comparatively low when compared to natural light under the same color temperature conditions, as shown in Fig. 1. Many existing LED lights, such as Light1, have very low R9 and R12, and even when the color rendering performance is improved to close to 90, such as Light2, R9 and R12 show low values of 71.6 and 66.7, respectively. In addition, although Light3 is a light developed to provide high color rendering performance, it does not provide the color rendering performance of natural light, with an R12 value in the 80s.

In this study, an attempt was made to achieve high color rendering by reflecting the wavelength characteristics of natural light in artificial lighting. Therefore, considering application to existing commercial lighting (Light1–Light3), LED light sources with peak wavelengths of 405 nm and 630 nm, which are known to be closely related to CRI in previous studies, were added. Spectra were generated by applying a Gaussian function of the following formula to AddLed1, an additional light source with a peak wavelength of 405 nm, and AddLed2, an additional light source with a peak wavelength of 630 nm. When developing LED lighting that reproduces the SPD characteristics of natural light, virtual LED light sources, AddLed1 and AddLed2, were employed to compensate for the SPD deficiencies. Experiments showed that using commercial LED light sources to address the insufficient SPD regions is sufficient to achieve high CRI.

$$f\left(x\right)=\frac{1}{\sqrt{2\pi\sigma}}\exp\left\{-\frac{\left(x-\mu\right)^{2}}{2\sigma^{2}}\right\} \tag{1}$$

where x denotes the wavelength (380–780 nm), μ represents the peak wavelength, and σ denotes the standard deviation.

In Eq. (1), by setting μ to 405 and 630 nm and σ to 6, a spectrum with a normal distribution pattern was generated for each 50-nm wavelength band, and the full width at half maximum (FWHM) was approximately 18.84 nm. In addition, the SPD for gradual current control was calculated by multiplying the Gaussian function result by the ratio to the maximum spectral irradiance. Each light source channel was controlled to optimally match the spectral ratio of natural light by gradually increasing and decreasing the spectra of the additional light sources in accordance with the color temperature control of Light1 to Light3 [28]. Table 3 provides an example of the step-by-step execution of spectral simulation, showing the result of adding the spectral values of 2,700 K and 6,500 K LED light sources with AddLed1. Figs. 4 and 5 show the results of SPD simulation using the proposed method.

Table 3 Example of step-by-step execution of SPD simulation

LED1 2,700 K and LED2 6,500 K, step-by-step control of AddLed1 (405 nm)						
Step (W/m²)	Illuminance (lux)	CCT (K)	CRI	R9	R12	CQS
1 (0.000)	998.314	3,933.65	97.83	97.10	86.92	93.39
2 (0.001)	998.320	3,935.70	97.81	97.17	87.17	96.38
3 (0.002)	998.329	3,937.76	97.80	97.24	87.41	96.38
⋮						
40 (0.040)	998.669	4,018.84	96.72	97.67	95.72	95.69

In the proposed method, as shown in Fig. 4, the applied current for each light source of the two-channel LED system and the two types of AddLED1 and AddLED2, with peak wavelengths of 405 nm and 630 nm, was gradually controlled. The control step most similar to the wavelength ratio of natural light was derived under each natural light color temperature condition. Subsequently, control was performed for each LED channel, and the spectra were summed as shown in Fig. 5. Therefore, a development plan for LED lighting achieving high color rendering was presented by deriving and applying control conditions based on the spectral ratio of natural light under different color temperature conditions.

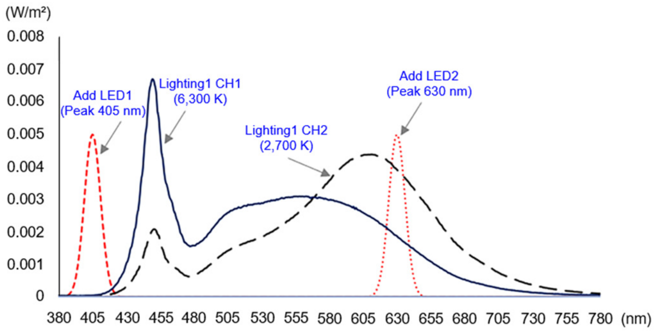


Fig. 4 Example of spectral simulation: Lighting1 + AddLEDs

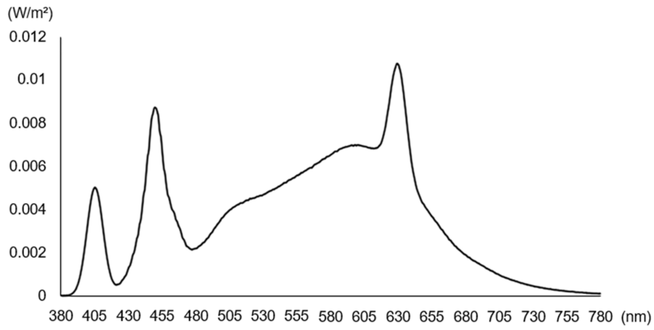
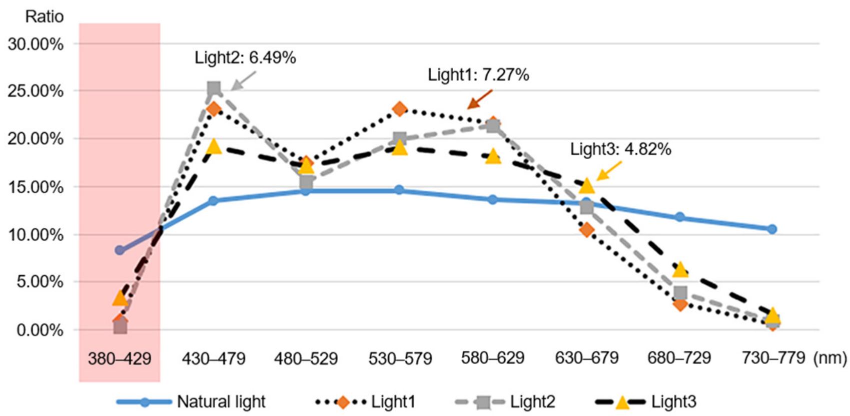


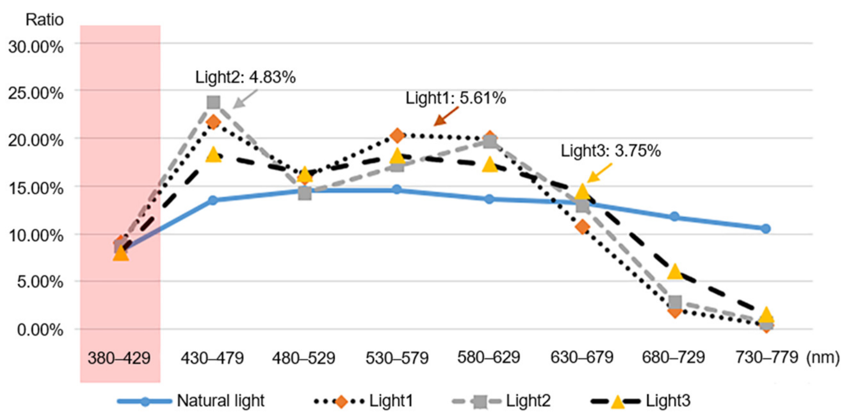
Fig. 5 Spectral simulation results

4. Experiment and Discussion

An experiment was conducted to determine whether it is possible to develop lighting with high color rendering performance through control based on the spectral ratio of each wavelength band of natural light. The experiment was performed on three types of LED lights, as listed in Table 1. Fig. 6 illustrates an example of the results obtained by applying the proposed method to Light1–Light3 at a color temperature of 5,500 K, with an emphasis on reproducing the spectral ratio for each wavelength band of natural light as accurately as possible.



(a) Before applying the proposed method



(b) After applying the proposed method

Fig. 6 Simulation results based on natural light SPD (5,500 K, Light1)

Fig. 6 shows the results before and after applying the proposed method. As shown in Fig. 6(a), the average error rates compared to the natural light spectrum of Light1–Light3 were 6.89%, 6.04%, and 4.23%, respectively. In the proposed method, additional light sources (AddLED1 and AddLED2) with peak wavelengths of 403 nm and 630 nm were applied, and the average spectral difference rates (SDRs) compared to natural light were reduced to 4.97%, 4.12%, and 3.00%, respectively. Overall, the SDR values did not show significant differences, which may be due to the fixed spectral characteristics in the 680–779 nm range, where spectral variations were difficult to control even with adjustments to the white LED light source. Through the proposed method, specific wavelength bands, such as 380–429 nm, were reproduced with spectral ratios similar to those of natural light. The proposed method was also applied under color temperature conditions of 4,500 K and 3,500 K, and the results are shown in Table 4.

Table 4 Results of the proposed method

Category	Control CCT	Before applying				After applying			
		SDR	CRI	R9	R12	SDR	CRI	R9	R12
Light1	5,500 K	7.27%	85.3	18.8	65.8	5.61%	92.8	78.8	76.4
	4,500 K	6.72%	87.1	29.6	67.5	6.60%	93.2	78.3	83.2
	3,500 K	8.85%	87.2	29.6	76.4	8.67%	94.8	81.3	87.4
	Average	7.61%	86.6	26.0	69.9	6.96%	93.6	79.5	82.3
Light2	5,500 K	6.49%	89.6	71.6	66.7	4.83%	91.0	92.4	70.2
	4,500 K	6.09%	89.3	68.1	65.9	5.92%	90.7	87.8	69.0
	3,500 K	8.46%	87.9	53.2	72.4	8.15%	89.1	62.7	74.0
	Average	7.01%	88.9	64.3	68.3	6.30%	90.3	81.0	71.1
Light3	5,500 K	4.82%	97.6	93.6	83.0	3.75%	97.7	95.1	85.4
	4,500 K	4.22%	98.2	98.3	82.4	4.63%	98.0	98.1	85.5
	3,500 K	6.79%	97.5	94.6	88.8	6.70%	97.4	94.9	90.1
	Average	5.28%	97.8	95.5	84.8	5.03%	97.7	96.0	87.0
Average		6.63%	90.8	58.2	75.7	6.10%	93.9	85.5	80.1

As shown in Table 4, Light1’s CRI improved significantly, including R9 and R12, under all color temperature conditions. When compared with the average values, the SDR with natural light decreased from 7.61% to 6.96%, while CRI increased from 86.6 to 93.6, R9 rose from 26.0 to 79.5, and R12 increased from 69.9 to 82.3. In addition, for Light2, the CRI increased to 90.3 (from 88.9), while SDR decreased to 6.30% (from 7.01%). Notably, R9 improved significantly to 81.0 (from 64.3). In the case of Light3, which had the highest average CRI among the experimental lights at 97.8, there was almost no difference in CRI; however, R9 and R12 showed slight improvements. Light1 showed the most significant improvement in the experiment, confirming that color rendering performance can be effectively enhanced when applied to general CRI 85 LED lighting.

Experiments have shown that it is possible to develop high-CRI artificial lighting by applying the spectral intensity ratio of each wavelength band of natural light. However, this approach targets the commonly used CRI in commercial lighting and does not consider more advanced color quality metrics, such as CQS and TM-30 color fidelity. In future studies on the commercialization of high-CRI lighting, it is necessary to explore and apply white LED light sources with more diverse peak-wavelength characteristics to more precisely match the spectral intensity ratios of natural light and to conduct performance evaluations based on these advanced color quality metrics.

5. Conclusions

This study proposed a method for developing natural light LED lighting, which utilizes high color rendering to reflect the spectral ratio characteristics of natural light. The main analysis and conclusions are summarized as follows:

(1) Analysis of clear daytime conditions across all seasons revealed that natural light achieved a CRI of 91 or higher, with an R9 value of 53 or higher and an R12 value of 90 or higher, within the color temperature range of 3,000 K to 6,000 K.

(2) A comparative analysis of three types of commercial LED lighting (denoted as Light1, Light2, and Light3), which allowed for controllable color temperatures, revealed that while these LEDs had a high CRI of 85 or higher, their R9 and R12 values were significantly lower, measuring 18.8 and 65.8, respectively.

(3) To achieve a spectral ratio similar to that of natural light, a virtual LED light source was generated with peak wavelengths at 405 nm and 630 nm. Simulations were conducted to incorporate the spectrum of each LED channel, thereby enhancing the spectrum in the 380–429 nm band.

(4) The performance evaluation indicated that applying this method improved the CRI, R9, and R12 color rendering capabilities to 93.9, 85.5, and 80.1, respectively (up from 90.8, 58.2, and 75.7) for existing LED lights with CRIs of 85, 90, and 95. In particular, the LED lighting with a CRI of 85 showed a significant increase to 93.6, along with R9 and R12 values of 79.5 and 82.3.

In future work, research will be conducted to apply the spectral ratio of natural light to wavelength regions beyond the 380–429 nm band, where accurately reproducing natural light characteristics remains challenging due to the inherent limitations of commercial LED light sources.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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