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CRI-Based Smart Lighting System That Provides Characteristics of Natural Light

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Abstract: Natural light continuously changes its correlated color temperature (CCT) from sunrise to sunset, providing the best color reproducibility and healthy light. In the lighting field, efforts have been made to improve the Color Rendering Index (CRI) to provide light quality at the same level as natural light. A unique light source technology that mixes and controls multiple LED light sources with different spectral or CCT characteristics or provides a high color rendering index has been introduced. However, the characteristics of natural light, which provide high CRI light while changing color temperature every moment, could not be reproduced as they were. Therefore, in this paper, we propose a CRI-based smart lighting system that reproduces natural light characteristics, provides light with high color reproducibility, and maintains homeostasis even under the changing environment of natural light CCT. After extracting the CCT for each day from the characteristics of measured natural light, the light with the highest CRI under the CCT condition for each hour was provided through a CRI-based CCT matching algorithm. Performance evaluation was conducted for four-channel LED experimental lighting. For each clear and cloudy day, daily natural light was reproduced with a light quality higher than average CRI 98 within the MAE range of CCT 6.78 K.

Keywords: CRI; smart lighting system; natural light; LED; correlated color temperature (CCT)

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1. Introduction

Smart lighting technology that provides beneficial light to humans by reflecting the characteristics of natural light is emerging [1–3]. Natural light provides the ideal light to recognize the natural color of objects and is most beneficial to human health [4]. Natural light contains the complete color spectrum in the visible light band and is the light with the best color expression [4,5]. It is also known that the dynamic color change of natural light positively affects human health [6]. The most common criterion for evaluating the color reproducibility of light is the Color Rendering Index (CRI) [7]. CRI measures how well a target light source can express colors compared to light from a reference source, such as natural light or a blackbody, under the same color temperature conditions [8,9]. Natural light is applied as a reference light with a CRI of 100 [10,11]. As described above, natural light provides humans with the most optimal light in terms of visual and non-visual aspects and color quality. However, modern people spend much time indoors under artificial lighting, which cannot ideally provide periodic changes and high color reproducibility like natural light [1,12]. Therefore, it is necessary to develop lighting that can provide an artificial lighting environment similar to natural light to improve visual comfort, work efficiency, and health in indoor workplaces or at home [3]. As the advantages of LED lighting with a long lifespan and low power consumption are highlighted, LED lighting has become common in various fields [12]. However, general LED lighting in the past often had a CRI of less than 80 and thus could not provide the same color reproduction as natural light [13,14]. The European standard for indoor lighting (EN 12464) recommends lighting with a CRI higher than 80 [15]. In addition, the Well Building Standard proposed higher lighting quality standards (CRI higher than 90) [15,16]. As the quality performance standards of lighting are stricter, the CRI of LED lighting is gradually improving, but it is still not capable of reproducing the realistic CRI performance of natural light.

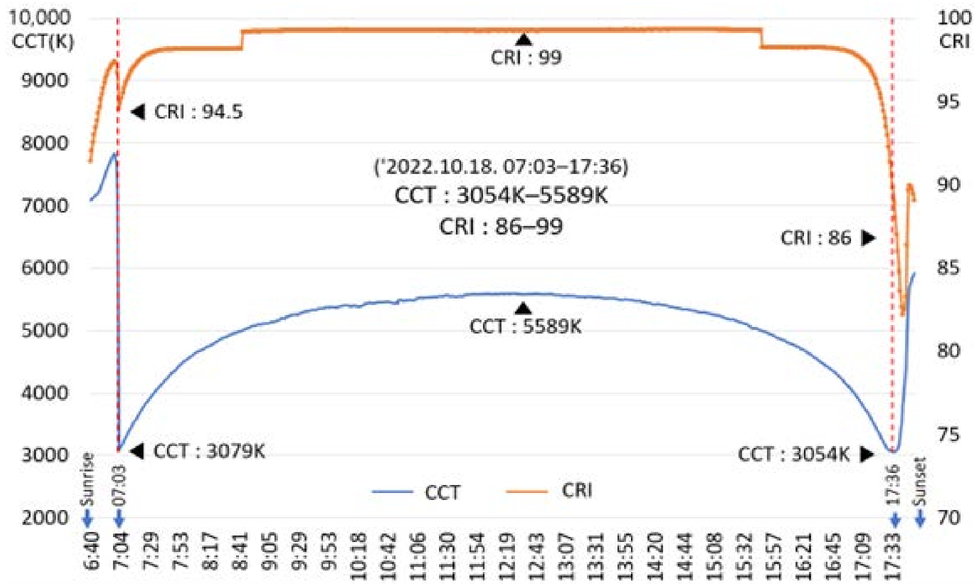
Recently, research has been conducted on LED light sources to realize similar light quality based on the CRI of natural light [11]. Oh et al. applied four LED light sources with assorted color characteristics to produce LED lighting that satisfies a CRI above 90 [17]. Zhao et al. introduced a technology that helped achieve a color rendering index higher than 98 under specific color temperature conditions through Smart quantum dot LED [18]. In addition, lighting companies have released LED light sources with a CRI higher than 95 to realize a spectrum like natural light [19]. However, natural light shows a correlated color temperature (CCT) value of about 2900 K at sunset and about 6000 K or more at noon on a clear day [20]. Natural light provides high CRI light under different light and color conditions every moment. Still, previous lighting technologies only tried to improve CRI. Nie et al. introduced a method of providing dynamic CCT while maintaining high CRI by applying a five-channel LED light source of RGBWW [21]. Dai et al. achieved a CRI of 85–90 under various CCT conditions of 4000 K, 6500 K, 8000 K, and 13,000 K through lighting using a RGBW LED light source [22]. However, these technologies could only provide high CRI light under a few color temperature conditions and did not fully implement the dynamically changing natural light. It was unable to consistently provide a CRI higher than 95 under the conditions of dynamic color temperature change. There have been a few technical attempts to provide high CRI light with excellent color reproducibility like natural light and maintain homeostasis even under light color conditions that vary every hour in the morning, noon, and evening. Hence, at present, related research is lacking.

Accordingly, this paper proposes a CRI-based natural lighting system that provides light with high color reproducibility and maintains homeostasis even in an environment where natural light CCT changes over time. First, natural light's CRI and dynamic CCT characteristics were analyzed using the natural light characteristic big data DB collected by measurement. Through this, the CRI control standard was established, and the CCT cycle for each season was extracted to provide the time-dependent changing characteristics of natural light. In addition, the light characteristic information of illuminance, CRI, and CCT for each step of controlling the applied current of the LED light source channel of artificial lighting was measured and collected. Then, when CCT information for each solar term day was input, the control index of artificial lighting was extracted through the CRI-based CCT matching algorithm. By applying it to the control of artificial lighting through wireless control, a smart lighting system that provided light with a CRI of more than 95 under the dynamic CCT condition of natural light was developed.

2. Materials and Methods

2.1. Analysis of CRI and CCT Characteristics of Natural and Artificial Lights

To reproduce the characteristics of natural light based on CRI, the leading light characteristics of natural and artificial lights were compared. The research team used a spectroradiometer (CAS 140CT, Instrument Systems, Munich, Germany) at 36.85 latitude and 127.14 longitude to measure optical properties such as spectral power distribution (SPD), correlated color temperature (CCT), and CRI of natural light. A spectroradiometer was installed inside an enclosure equipped with a constant temperature function on the rooftop of an 8-story building, and the light-receiving unit was mounted on a solar tracking facility at a height of about 2 m from the rooftop floor. All the obstacles were removed from near the light-receiving unit. Since 2017, the characteristics of natural light have been continuously measured and collected to build a Hadoop-based natural light big data DB. By extracting the light characteristic data for each sunny and cloudy day from the natural light big data DB, daily CRI and CCT were compared and analyzed. Figure 1 shows the comparison results of natural light characteristics from sunrise to sunset. The clear days and cloudy days were distinguished by referring to the literature, which identified the anomalies as the color temperature difference at 1-min intervals higher than 50K [23]. Days with anomalies less than 5% were classified as clear days and as cloudy days otherwise. Figure 1 shows the results of comparing natural light characteristics from sunrise to sunset.



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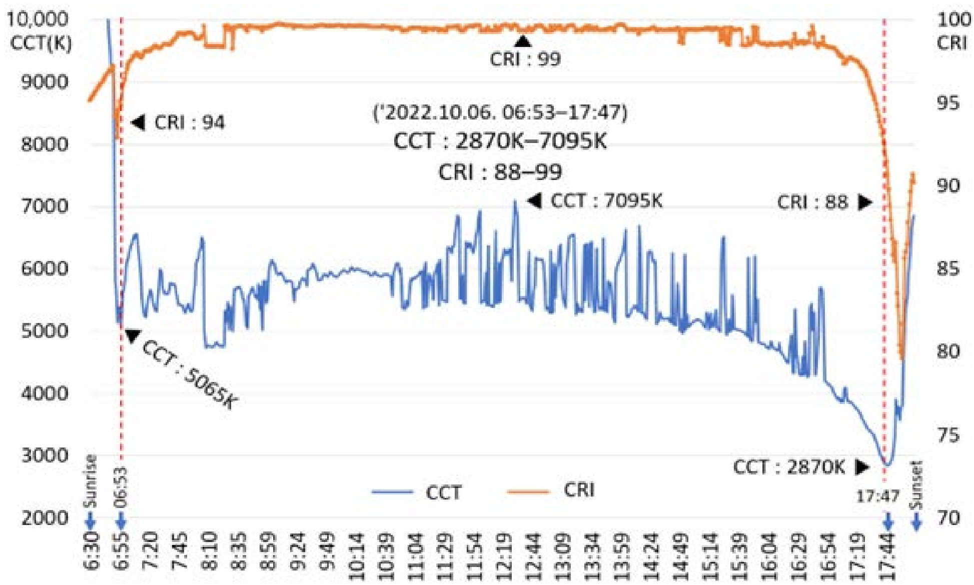


(**b**)

Figure 1. CCT and CRI characteristics of natural light. (**a**) Clear day (Anomalies 5%): '2022.10.18; (**b**) Cloudy day (anomalies 30%): '2022.10.06.

As shown in Figure 1, sections where the CRI and CCT abruptly increased or decreased were observed briefly around sunrise and sunset. The zone was when only a part of the sun was visible on the ground around sunrise and sunset, or when the evening was visible. Therefore, the period between sunrise and sunset with the lowest CCT was the circadian period of natural light. The circadian characteristics of natural light showed a CRI of 86–99 and CCT characteristics ranging from 3054 K to 5589 K on a clear day in Figure 1a. Even on a cloudy day, in Figure 1b, high CRI characteristics of 88–99 were observed, and the CCT was 2870 K to 7095 K, slightly higher and broader than that of a bright day. On a cloudy day, the distribution of CCT was unbalanced, so it seemed unsuitable to apply to the reproduction of the daily natural light cycle. As shown in Figure 1, natural light maintains a CRI of 86 to 99 even under various CCT conditions on a bright or cloudy day, leading to a high CRI of 99 in the time zone of about 9 to 16 o'clock. At this time, a zone where CRI changed rapidly and discontinuously in the morning and afternoon was observed in Figure 1a, which might be a characteristic of the spectral-based CRI calculation formula built in the spectroradiometer (CAS 140CT).

To refer to the control standard setting of LED lighting, the universally used optical characteristics of artificial light were compared and analyzed. Here, control standards were set for objectively comparing natural and artificial lights. The light characteristics of each light source were measured and compared under the condition that the general CCT of artificial light, 5500 K, and the illuminance of 450 Lux, which corresponded to the recommended illuminance standard (300–600 Lux, KSA 3011A) of the domestic general office environment, were met as much as possible. The spectral and CRI characteristics of Company K's natural light, ordinary office LED lighting, multi-channel LED lighting, and Company D's natural light reproduction LED lighting were analyzed. The results are shown in Figure 2.

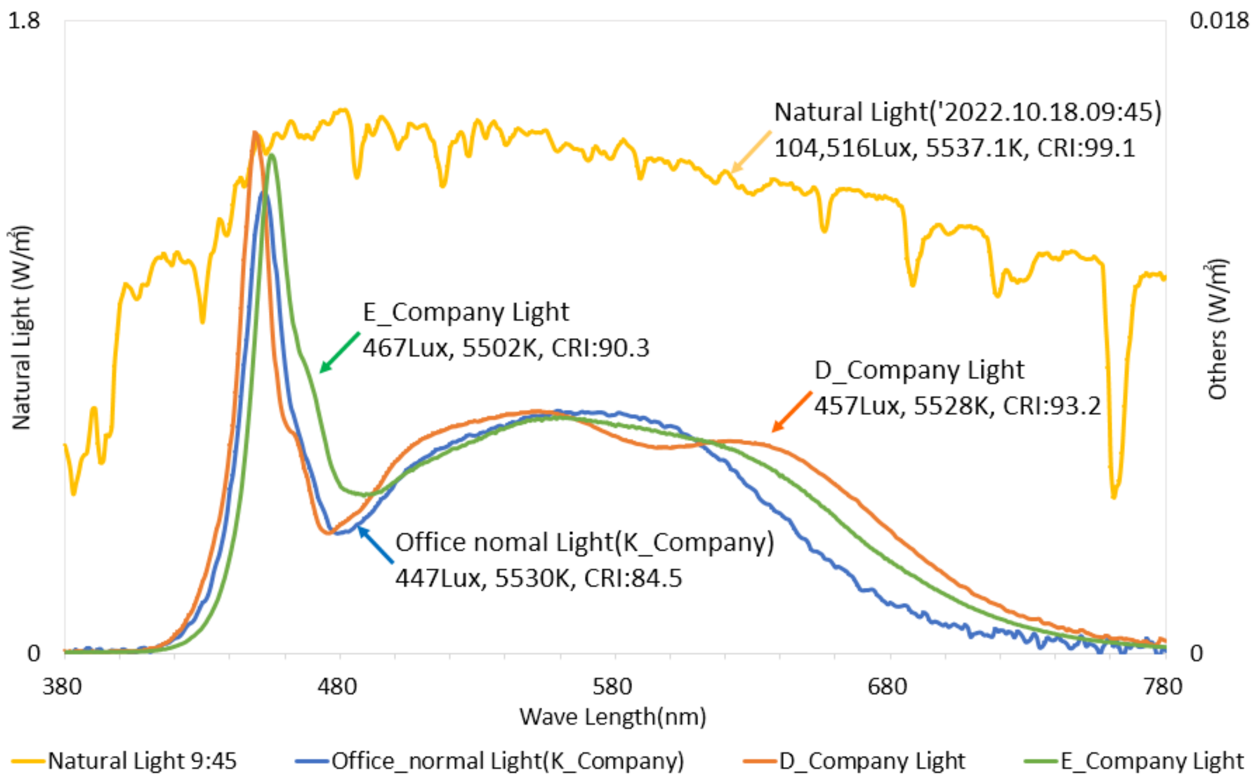


Figure 2. Comparative analysis of light characteristics between natural light and artificial light.

As shown in Figure 2, the natural light spectrum was evenly distributed over the entire visible light range. Still, the three types of artificial lighting showed a high specific wavelength band and an uneven distribution compared to natural light. The spectral irradiance in the band of about 450 nm was exceptionally high. The lighting from Company D (Dyson, Singapore, Singapore) had a slightly wider wavelength range around 600 nm than the other lights. The CRI of K (Keumkang Enertech, Siheung, Republic of Korea) company's ordinary office lighting was low at 84.5. D company's lighting and E (Entec, Hwaseong, Republic of Korea) company's multi-channel led lighting were 93.2 and 90.3, respectively, higher than those of K company's ordinary office lighting. In Figure 2, some artificial lights provided light quality with a significantly lower CRI than 99.1 natural light, although higher than the CRI of 80 for general LED lights [24,25]. In addition, it was found that the spectral (SPD) and CRI of artificial lighting were different even under the same color temperature conditions. The artificial lighting that reproduces the characteristics of natural light should provide high CRI not only in specific colors but also in various dynamic color conditions of natural light.

2.2. CRI-Based Natural Light Reproduction Smart Lighting System

This paper proposes a smart lighting system that provides optimal CRI light even when the CCT of natural light changes over time for the realistic reproduction of natural light. The CRI-based natural light reproduction smart lighting system was linked with the natural light big data DB built by collecting measured data in advance to reproduce the characteristics of natural light with high accuracy. The proposed system derived the CCT control conditions of natural light by time by analyzing the CCT characteristics through the CRI-based CCT matching algorithm and extracted the control index of LED lighting necessary to provide light with high color rendering under their respective CCT conditions. Figure 3 shows the primary process of the proposed system.

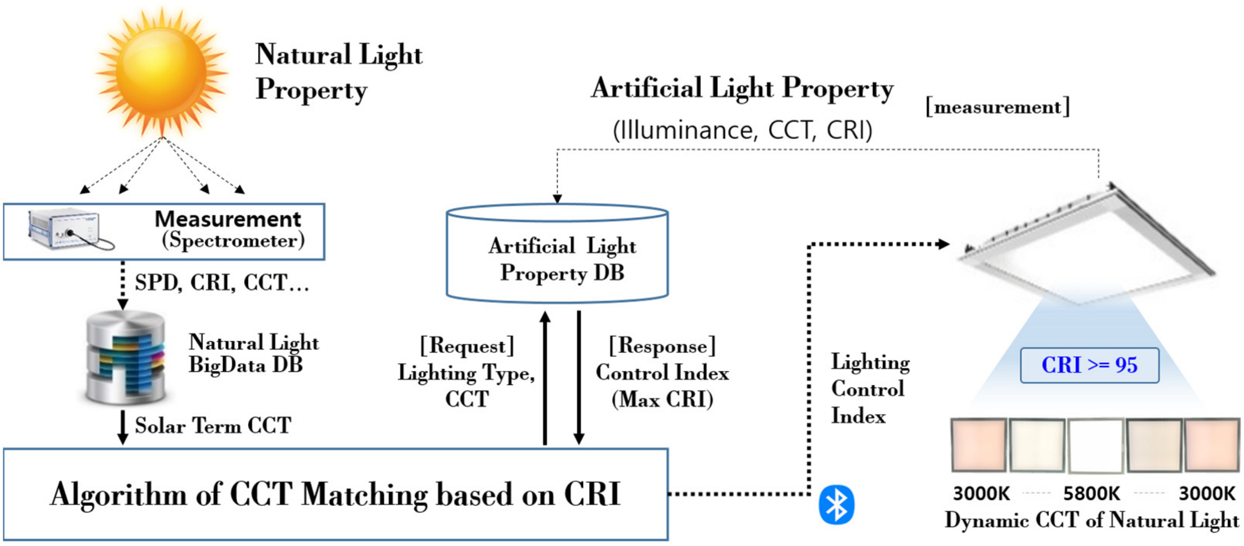


Figure 3. CRI-based natural light reproducing smart lighting system.

2.2.1. Natural Light Big Data DB and Artificial Light Property DB

To realistically reproduce natural light through artificial lighting, reliable natural light characteristic data as a reference is required. This study utilized the natural light big data DB introduced in Section 1. In the natural light big data DB, light characteristic information, such as SPD, CRI, CCT, and Illuminance of natural light, measured every 1 min for each day of the year, was stored. For this purpose, the characteristics of natural light collected by applying a spectroradiometer (CAS 140 CT, Instruments, Germany) and a solar tracking device were measured and analyzed from April 2017 to July 2023 (6 years and 4 months). To realize the level of natural light, it is necessary to provide high CRI under dynamic CCT conditions of natural light that constantly change due to the Earth's rotation and revolution. In addition, since a stable natural lighting service should be provided even on cloudy days, the standard CCT cycle for every 24 solar terms was extracted. In this case, by referring to previous research on natural light lighting systems, a bright day in each solar term was selected and a color temperature cycle was created using the color temperature value every minute [26]. The proposed system reproduced the characteristics of natural light with a high CRI regardless of the change of clear and cloudy weather by providing the reference CCT cycle of the season closest to the subject day. Table 1 shows a natural light big data DB, and Table 2 provides an example of the result of extracting the color temperature cycle for each solar term.

Table 1. Example of natural light big data DB.

Category	**Irradiance/nm (W/m^2)**								**Light Property**					
Time	380.1	380.7	381.4	...	778.8	779.5	780.1	780.8	Illuminance	CCT	CRI	...	u	v
7:01:49	0.014	0.013	0.013	...	0.019	0.019	0.019	0.019	2006.94	7624.16	97.2476	...	0.18951	0.46086
7:02:51	0.014	0.014	0.013	...	0.023	0.023	0.023	0.023	2123.88	7200.16	96.7116	...	0.19223	0.46367
7:03:56	0.016	0.015	0.015	...	0.464	0.465	0.464	0.467	13,486.7	3079.48	94.5417	...	0.24740	0.52138
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
12:14:54	0.726	0.710	0.674	...	1.141	1.140	1.137	1.134	114,441.	5584.46	99.2556	...	0.20481	0.47827
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
17:37:05	0.013	0.013	0.012	...	0.291	0.291	0.292	0.294	5929.68	3063.80	88.0367	...	0.25087	0.51070
17:38:08	0.012	0.012	0.011	...	0.270	0.270	0.271	0.272	5262.98	3077.25	87.0122	...	0.25081	0.50910

Table 2. Example of CCT cycle for each of the solar terms.

Category		**Daily CCT Cycle**											
Onset of spring	Time	8:03	8:04	8:05	8:06	...	12:43	12:44	...	17:33	17:34	17:35	17:36
('2022.02.10)	CCT	3703.55	3698.30	3699.96	3707.33	...	5579.75	5565.10	...	3575.91	3570.23	3582.91	3610.59
...	...	...	...	...	...	...	...	...	...	...	...	...	...
Major cold	Time	8:03	8:04	8:05	8:06	...	12:28	12:29	...	16:49	16:50	16:51	16:52
('2021.12.22)	CCT	3399.75	3184.36	3148.35	3175.98	...	5151.65	5170.22	...	3265.02	3259.90	3289.13	3303.31

In addition, to control artificial light based on CRI and color information of natural light, light characteristic details on artificial light are needed. In the preceding studies, a method for calculating CCT according to the control of each light source channel was introduced by computing the spectral and CCT features of LED light sources constituting artificial lighting [27,28]. However, since various CRI characteristics can be expressed even under the same CCT condition, the light properties of artificial lighting were collected through measurement for more accurate control, and the light property DB of artificial lighting was secured. Table 3 shows examples of light properties for each detailed control step constituting the artificial light property DB of artificial lighting.

Table 3. Artificial Light Property DB (Examples of light properties for each detailed control step).

LED Control Level				**Irradiance/nm (W/m^2)**							**Light Property**			
Ch1	Ch2	Ch3	Ch4	380	381	382	...	778	779	780	Illum	CCT	CRI	...
0	0	0	16	1.37×10^{-7}	8.68×10^{-8}	3.33×10^{-7}	...	4.42×10^{-6}	4.60×10^{-6}	4.30×10^{-6}	9.121396	5642.514	97.02109	...
0	0	0	32	1.58×10^{-6}	1.84×10^{-6}	1.60×10^{-6}	...	2.11×10^{-5}	2.09×10^{-5}	2.07×10^{-5}	41.14666	5637.386	97.12691	...
0	0	0	64	4.24×10^{-6}	3.96×10^{-6}	3.63×10^{-6}	...	4.88×10^{-5}	4.79×10^{-5}	4.53×10^{-5}	91.1695	5640.55	97.12795	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
208	32	0	0	2.24×10^{-5}	1.97×10^{-5}	2.38×10^{-5}	...	0.000356	0.000346	0.000342	677.8072	4590.438	96.31683	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
240	0	0	0	2.19×10^{-5}	2.36×10^{-5}	2.21×10^{-5}	...	0.000398	0.000387	0.000387	756.5922	4497.759	96.26328	...
255	0	0	0	2.55×10^{-5}	2.38×10^{-5}	2.66×10^{-5}	...	0.00046	0.000447	0.000439	871.5025	4500.924	96.24231	...

In the proposed method, the light properties of natural light and artificial light were informatized as shown in Tables 1 and 3, and the control index of LED lighting that could provide the most similar daily CCT cycle of Table 2 was searched. Through this, a CRI as high as natural light was provided while maintaining the CCT cycle of natural light.

2.2.2. CRI-Based CCT Matching Algorithm

A CRI-based CCT matching algorithm was developed and applied to provide high CRI light even under changing color conditions in natural light. When the usage time of lighting was input, the time-specific CCT of the nearest solar term was searched and loaded from the natural light big data DB. Afterward, control indices for each channel of LED lighting capable of realizing the corresponding CCT and optimal CRI were extracted from the optical characteristic DB of artificial lighting. The central processing flow of the CRI-based color temperature matching algorithm is shown in Figure 4.

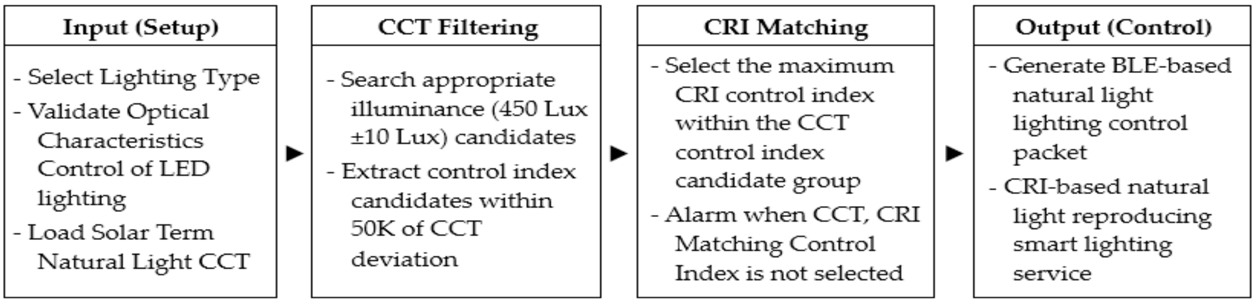


Figure 4. The primary process of the CRI-based natural light characteristic matching algorithm.

As shown in Figure 4, for the CRI-based natural light characteristic matching algorithm, the LED lighting and color temperature cycle were set first in the input stage. The proposed method can be applied to LED lighting with multi-channels that can be controlled for each LED channel. In this study, 4-channel LED lighting using two types of WW (Warm White) and WC (Warm Cool) LEDs was used to provide the low and high color ranges of natural light based on the CCT. For the proposed method, its applicability to commercial general-type lighting is an important consideration. Therefore, color LEDs and light sources with specific wavelength band characteristics, which were used in some studies to improve CRI, were excluded, and four-channel LED lighting was fabricated by applying easily available commercial LED light sources. The light characteristic control validation was first performed when the control target LED lighting was designated. The lighting could control the CCT range of natural light and the CRI $\geqq$ 95 condition. At this time, the CCT range may differ for each season, but the minimum threshold of CRI was set at 95. Afterward, in the CCT filtering step, lighting control index candidates that provide hourly CCT were extracted through the light characteristic DB of LED lighting. Control indicators capable of providing illumination of 450 $\pm$ 10 Lux were first searched to qualify for the domestic recommended illuminance standard (300–600 Lux, KSA 3011A). Then, a candidate group of lighting control indicators applicable within the critical range of hourly CCT was extracted. The critical range of CCT was set to $\pm$50K by referring to a previous study that analyzed the difference in CCT at 1-min intervals of natural light [29]. Afterward, in the CRI matching process, the control index with the highest CRI was selected among the CCT control index candidates. In the natural light analysis in Section 2, the CRI was decreased to less than 90 in certain time zones around sunrise and sunset. However, in this study, the control index of the maximum possible CRI condition was selected even when the CRI of natural light was low. Through this, it was aimed to provide optimal CRI light in all time zones. When the lighting control index was selected through CCT filtering/CRI matching, a BLE (Bluetooth Low Energy)-based lighting control packet was created in the output stage for wireless LED lighting control. Afterward, LED lighting was controlled to provide a natural lighting service that satisfied high CRI and the color change of natural light. Through this, a smart natural light lighting system was developed that reproduced natural light every minute through the big data DB built in connection with the sensing technology.

3. Experiments and Discussion

To check the performance of the proposed system, experimental lighting was fabricated, and its ability to provide light with CRI-based natural light quality was evaluated. The practical lighting consisted of four LED light source channels of 2700 K, 4500 K, 5700 K, and 6500 K. All applied light sources were SunLike (Seoul Semiconductor, Korea) products of S Company. The CRI was about 96, and each peak wavelength was 628, 455, 455, and 455 nm. In addition, an AC/DC converter with a constant current output standard of 50 W was adopted to supply power to the LED array module of the experimental lighting, and a drive control unit (Four-Channel Driver Controller) was fabricated and applied to control each channel of the LED array module. The LED array module could adjust the input current from 0–255 for each channel. For the experiment, experimental lighting was installed at the top of the lighting cabinet that blocked external light, and the lighting was controlled by increasing the input current by 16 for each channel. Additionally, a spectroradiometer (CAS 140CT) was installed at a vertical distance of 150 cm from the lighting to measure optical characteristics. The optical characteristics measured for each input current control condition were made as a database and used as a lighting control index. Figure 5 shows the measurement results of the characteristics of the experimental lighting and the light properties for each detailed control step.

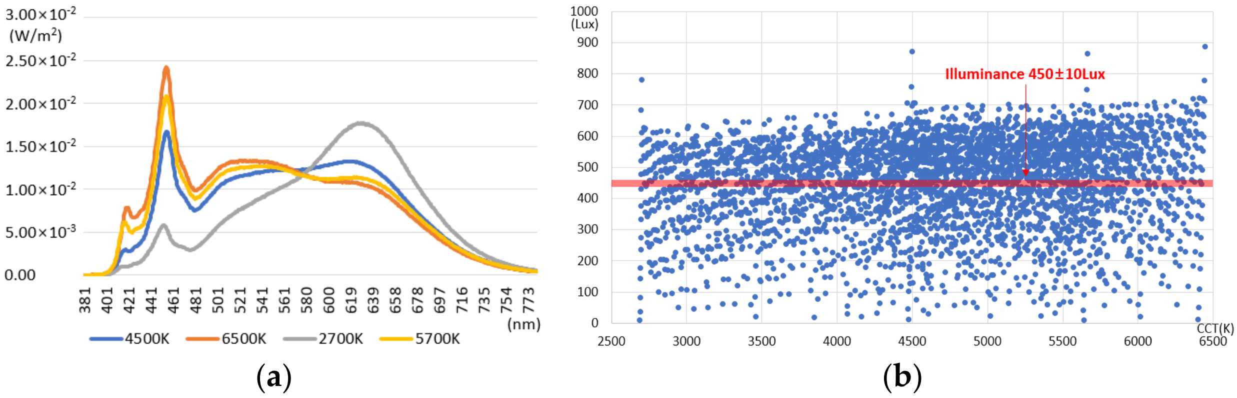


Figure 5. Measurement results of light characteristics by control stage of experimental lighting. (**a**) Spectrum by channel of LED light; (**b**) CCT and Illuminance (Search appropriate illuminance candidates).

Figure 5a shows the spectrum of the applied light source, and all LEDs for each channel are widely distributed in the visible light band. When the spectral characteristics of artificial lighting in Chapter 2 were compared, it would be advantageous to reproduce natural light with a pattern closer to natural light. Figure 5b shows the distribution of illuminance and CCT for each channel and a detailed control step. It provided light in the color temperature range of 2700 to 6500K and the illuminance range of 0 to 700 Lux. In Figure 5b, the red line indicates the control candidate group capable of providing an appropriate illuminance of 450 ± 10 Lux. Based on the results, the implementation result of the CRI-based CCT matching algorithm is shown in Figure 6.

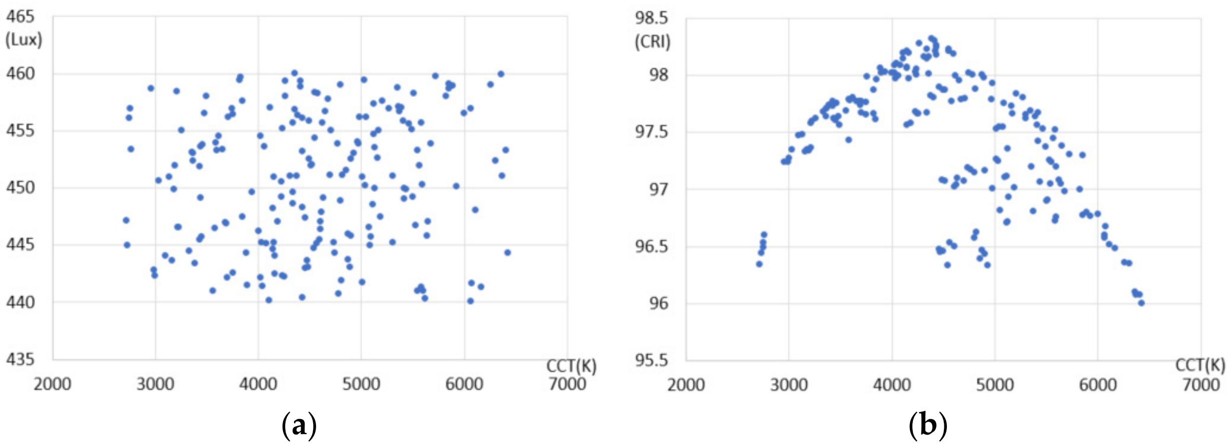


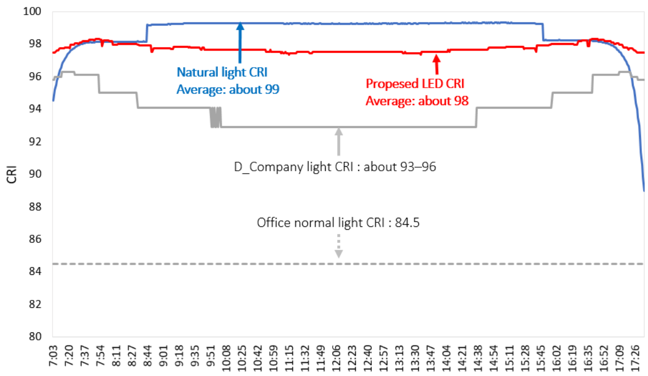
Figure 6. Measurement results of light characteristics for each control stage of experimental lighting. (**a**) CCT and Illuminance for CCT filtering; (**b**) CCT and CRI for CRI matching.

Figure 6a is a search result for a control candidate group capable of providing an appropriate illuminance level. Afterward, the lighting control conditions that provided the best CRI light under specific color temperature conditions were selected from the optical characteristics of each control step in Figure 6b. Illuminance was controlled by extracting the control index, which provided the respective CCT and CRI.

To evaluate the performance of the proposed method, a bright day (18 October 2022) and a cloudy day (6 October 2022) in Figure 1 were selected. To control the color temperature by the hour for the selected days, the color temperature cycle of each solar term adjacent to the selected day was extracted from the natural light big database. The color temperature cycle for each clear day of the season (17 October 2022 and 13 October 2022) corresponding to each selected date was extracted. Afterward, the control index of LED light that could provide CRI of natural light level when providing the extracted color temperature by time was explored and applied to the control of experimental lighting. In addition to the in-house-fabricated experimental lighting, a comparative experiment was conducted with the existing artificial lighting introduced in Section 2.1. The experiment was conducted in a lighting cabinet where external light was blocked. A light was installed at the top of the lighting cabinet, and a spectroradiometer (CAS 140CT, Instrument Systems, Munich, Germany) was installed at the bottom. The distance between the lights and the spectroradiometer was maintained at 150 cm, and the spectra, illuminance, color temperature, and CRI at the control stage of each light were measured. The results of applying the proposed method and controlling existing artificial lighting are shown in Figures 7 and 8. Figure 7 shows the results of applying the proposed method on a clear day (18 October 2022), comparing the difference with the hourly CRI of natural light.

Time	Natural Light	Propesd Method	Absolute Error
7:03:56	3079.49	3099.21	19.72
7:04:59	3120.93	3139.55	18.61
7:06:02	3154.17	3165.65	11.48
---	---	---	---
12:00:10	5574.61	5573.59	1.02
12:01:13	5585.04	5592.55	7.52
12:02:16	5581.68	5573.59	8.09
---	---	---	---
17:33:56	3067.07	3035.55	31.52
17:34:59	3057.65	3035.55	22.09
17:36:02	3054.44	3035.55	18.89
MAE(Mean Absolute Error)			**6.79**

(**a**)

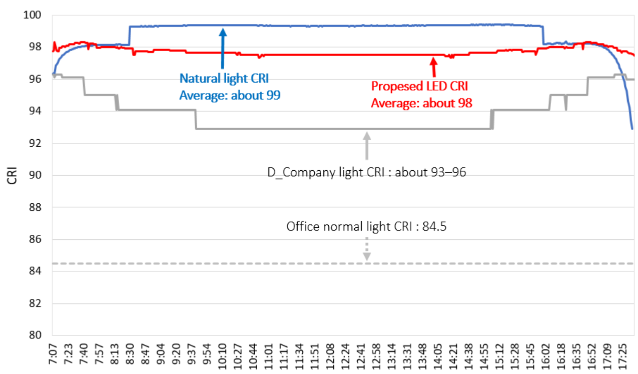


(**b**)

Figure 7. Natural light reproduction result: a clear day. (**a**) CCT; (**b**) CRI.

Time	Natural Light	Propesd Method	Absolute Error
7:07:01	3511.63	3497.56	14.07
7:08:04	3632.07	3624.36	7.71
7:09:07	4340.83	4340.68	0.15
---	---	---	---
12:00:44	5619.86	5624.86	5.00
12:01:47	5618.84	5624.86	6.02
12:02:50	5619.73	5624.86	5.13
---	---	---	---
17:37:17	3189.49	3184.14	5.36
17:38:20	3174.45	3165.65	8.79
17:39:23	3162.43	3165.65	3.22
MAE(Mean Absolute Error)			**6.76**

(**a**)



(**b**)

Figure 8. Natural light reproduction result: cloudy day. (**a**) CCT; (**b**) CRI.

As shown in Figure 7a, the color temperature cycle of natural light over time was reproduced within the range of the average absolute error of 6.79K. Figure 7b shows the comparison results of the reproduction performance of natural light CRI. Company D's lighting showed a CRI value of 93–96 under the condition of providing the color temperature of natural light over time. For comparison, the CRI (84.5) of general office lighting is also displayed. However, the proposed method provided illumination light with an average CRI of 98 or higher. Especially during the daytime when the color temperature increased, the CRI of Company D's lighting was approximately 93, but the proposed method maintained a CRI of approximately 98. Figure 8 shows the results of an experiment on a cloudy day.

The results in Figure 8a show the reproduction of the CCT cycle of natural light within the range of an average absolute error of 6.76 K. The data in Figure 8b shows that providing a light environment close to the average CRI of natural light 98 on that day was possible. The CRI of Company D's lighting and general office lighting was similar to the results in Figure 7. Through Figures 7 and 8, it was confirmed that the proposed method provided illumination with a CRI at the level of natural light that was superior to that of existing commercial lighting. High CRI performance, closest to natural light, was maintained even at a CCT higher than 5000 K. Through the above process, it was possible to reproduce realistic natural light characteristics by providing time-varying color and high natural light CRI. In this study, a methodology for developing general lighting that drastically improves CRI in connection with sensing information about natural light characteristics was presented. However, at noon, when the color temperature was about higher than 5000 K, there was still a discrepancy of an average of 1 from the CRI of natural light. In addition, the CRI of the light environment of an indoor space where changing natural and artificial light were mixed could not be considered. To overcome these limitations, if we explore and apply LED light sources that can reinforce specific wavelength bands and link deep learning techniques, such as reinforcement learning, in the future, it will be possible to reproduce more realistic natural light characteristics.

4. Conclusions

Recently, research on lighting has continued to improve the quality of LED lighting and has realized high color reproducibility like natural light. A unique light source with high CRI or LED lighting technology that recognizes mixed control of LED light sources has been proposed. Still, it could not reflect natural light's continuously changing CCT. Accordingly, in this paper, a CRI-based smart lighting system that reproduces natural light characteristics, providing light with high color reproduction performance and maintaining homeostasis, like natural light, even in an environment where natural light CCT changes every moment, is proposed. First, to give a dynamic color change environment for natural light, the CCT cycle for each of the 24 seasons was derived by analyzing the big data DB of the measured natural light characteristics. In addition, a DB of light elements of artificial lighting composed of a combination of Warm White (WW) and Warm Cool (WC) LED light sources that realize natural light characteristics was constructed. In the optical characteristics DB of artificial lighting, the measured optical characteristics of illuminance, CCT, and CRI at each control step were stored while increasing the human current for each channel by 16 from 0 to 255. Then, a CRI-based CCT matching algorithm was applied. With the CCT matching algorithm, the control index of the LED lighting with the highest CRI, within 50 K of color temperature deviation, and 450 $\pm$ 10 Lux of illuminance was extracted when the CCT value for each hour was input. By applying this to the control of LED lighting and reproducing the CCT cycle for each of the 24 seasons, high CRI light was provided under the condition of changing the CCT of natural light. A method for realizing a smart lighting system that provides realistic natural light quality in connection with light characteristic sensing technology was presented. Experimental lighting was fabricated using 4 types of LED (Sunlike, Seoul Semiconductor, Republic of Korea) light sources with different light characteristics, and the reproduction performance of natural light characteristics was examined. By applying the proposed method to bright days and cloudy days, natural light features were reproduced with a light quality of an average of 98 of higher CRI while providing the changing colors of natural light within the range of 6.78 K average CCT error. In particular, the CRI of the existing artificial lighting became lower in the zone where the color temperature of natural light during the day was high, but the proposed method could maintain light with an average CRI of 98 or higher even at high color temperatures of over 5000 K. Therefore, it was confirmed that the proposed method could provide light at the level of natural light even under changing color conditions of natural light.

In the future, we will attempt deep learning-based lighting control technology based on special color rendering indexes such as R9 and R12 and spectroscopy in addition to the average color rendering index, which was not covered in this study. In addition, to improve CRI, we will conduct additional experiments with various LED light sources having specific peak wavelength characteristics and continue research for the commercialization of the proposed technology.

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