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Article

Selecting Energy-Efficient LED Retrofits with Optimal Color Qualities for New and Refurbished Buildings

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Abstract: This study carried out a literature search and selection in accordance with the PRISMA 2020 protocol to conduct a complete review of the literature describing the electrical, photometrical, and colorimetric parameters of LEDs. Based on it, a significant research gap was found in the field of LED-based lighting retrofits. We prove that there is a lack of publications indicating the relationship between the energy consumption of LED retrofits and user preferences concerning the quality of lighting. This article presents an effective new method for selecting LEDs to retrofit typical 3000, 4000, and 6500 K fluorescent lighting installations in buildings. It is shown that when selecting an LED replacement for a fluorescent source, consideration of the classically used parameters in the field of lighting technology to describe the quality of white light, specifically correlated color temperature and the color rendering index, is insufficient. We demonstrate that energy efficiency and the color preference criteria for retrofitted LEDs must be considered and balanced with the potential impact on circadian rhythms as assessed by the melanopic daylight efficacy ratio. This research proves that LED replacements with the best color preference properties (P1 class in the CPC classification of ANSI/IES TM30-20 method) correspond to the least energy-efficient light sources.

Keywords: retrofitting solutions; sustainable lighting; solid-state lighting; lamps; energy efficiency



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1. Introduction

Despite the growth of the solid-state lighting market based on LED lamps and luminaires, fluorescent lamps (FL) are still widely used in interior lighting applications, especially in public office buildings and schools. The spectral power distribution (SPD) of commercially available FLs includes several narrow spectral peaks due to mercury (Hg) emission lines and phosphor emissions (see Figure 1). However, various regulations are now being implemented across European Union (EU) countries aimed at phasing out environmentally harmful substances, including mercury [1]. As a consequence, the largest category of mercury-containing light sources has been prohibited in the EU for both renovated and new lighting installations since September 2023. The EU Restriction of Hazardous Substances (RoHS) directive will facilitate a global acceleration of the transition to energy-efficient, clean LED lighting through the United Nations Minamata Convention on Mercury [2]. It is not only the aforementioned legal requirements that are driving the replacement of fluorescent lamps with LEDs. Additionally, regulations concerning the energy efficiency of products [3–8] emphasize the need for installing energy-efficient lamps [9–11]

in indoor [12–14], outdoor [15–17], and transportation lighting applications [18–22]. Typically, 6500 K LEDs are used in industrial lighting like factories and high storage halls, 4000 K LEDs are used in public buildings such as schools and offices, and 3000 K LEDs are used in home lighting. As illustrated in Table 1, the luminous efficacy (LE [lm/W]) of LEDs is higher than that for FLs, indicating that LEDs consume less electricity than FLs to emit the same luminous flux. Solid-state lighting enables a more efficient use of power [23], which in turn contributes to a reduction in electricity bills and the carbon footprint [24]. This aligns with broader sustainability goals and environmental conservation efforts [25–27]. Table 1 also provides the luminous efficiency of radiation (LER) parameter, together with information about the lifetime of different types of light sources. The longer operational lifespan of LED products relative to FL is favorable and represents a relatively low-maintenance option for lighting installations [28]. LEDs are capable of achieving full brightness instantaneously [29], in contrast to fluorescent lights, which require a brief period of time to reach their maximum luminosity [30].

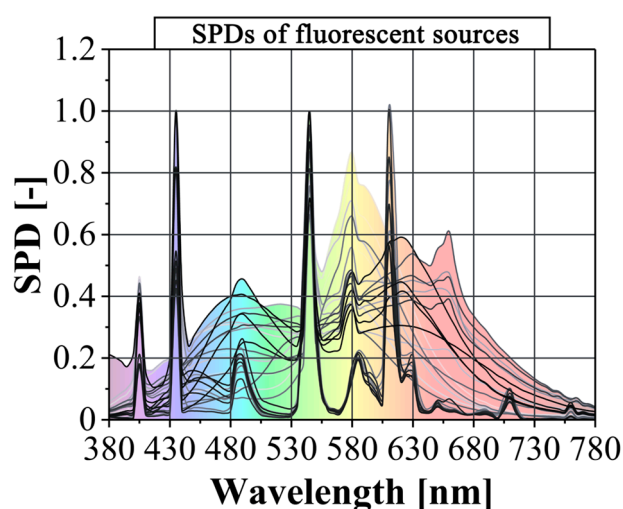


Figure 1. A set of typical relative SPDs of typical fluorescent lamps according to CIE [31].

A variety of techniques can be used to generate white light with LEDs. In most cases, combinations of different LED colors [32–34] or phosphor conversion techniques are used [33–38], leading to a broad range of possible spectral power distributions (SPDs). Each SPD is associated with a single set of values for luminous efficacy of radiation (LER) [lm/W] [39–42], correlated color temperature (CCT) [K] [43], and the color rendering index (CRI) [44,45].

The emission spectrum of a white phosphor-converted light-emitting diode (pc-LED) consists of a narrow primary peak in the blue or violet region and a broad secondary peak in the yellow-orange-red portion of the spectrum. The two peaks are separated by a region of minimal emission in the blue-green part of the spectrum. The white pc-LEDs first introduced by the Nichia corporation (see SPDs of LED-A shown in Figure 2a) use a yellow phosphor combined with a blue LED (with a peak wavelength of about 460 nm), emitting white light with a relatively low color rendering index (CRI) R_a , ranging from 60 to 70. However, the success of this type of LED is based on a relatively low cost and simplicity of manufacturing. The incorporation of a modest quantity of a red phosphor (see SPDs of LED-B in Figure 2a) enhances the R_a value to a level suitable for general lighting applications ($R_a > 80$) while improving the luminous efficacy of this type of LED [46]. A new generation of LEDs is based on violet light [47,48] and super-narrowband-emitting phosphors [49,50] (see SPDs of LED-C as illustrated in Figure 2a) to create white light with superior color parameters [51].

An alternative method for obtaining white light is the additive color mixing of LEDs (cm-LEDs). As is typical for this type of LED, the light produced by monochromatic red (R), green (G), and blue (B) diodes is mixed in appropriate proportions, resulting in white light (see SPDs of LED-D and LED-E in Figure 2b). However, LEDs based on the RGB technology often struggle to produce white light with acceptable color rendering [52]. To address this limitation, an additional amber diode (A) is incorporated into the RGB light source. White LEDs based on RGBA diodes (Figure 2c) have demonstrated the ability to achieve high CRI values and higher LER values [53]. Furthermore, other types of cm-LEDs are being developed with violet diodes instead of blue ones (see SPDs of LED-F in Figure 2b and SPDs of LED-I in Figure 2c).

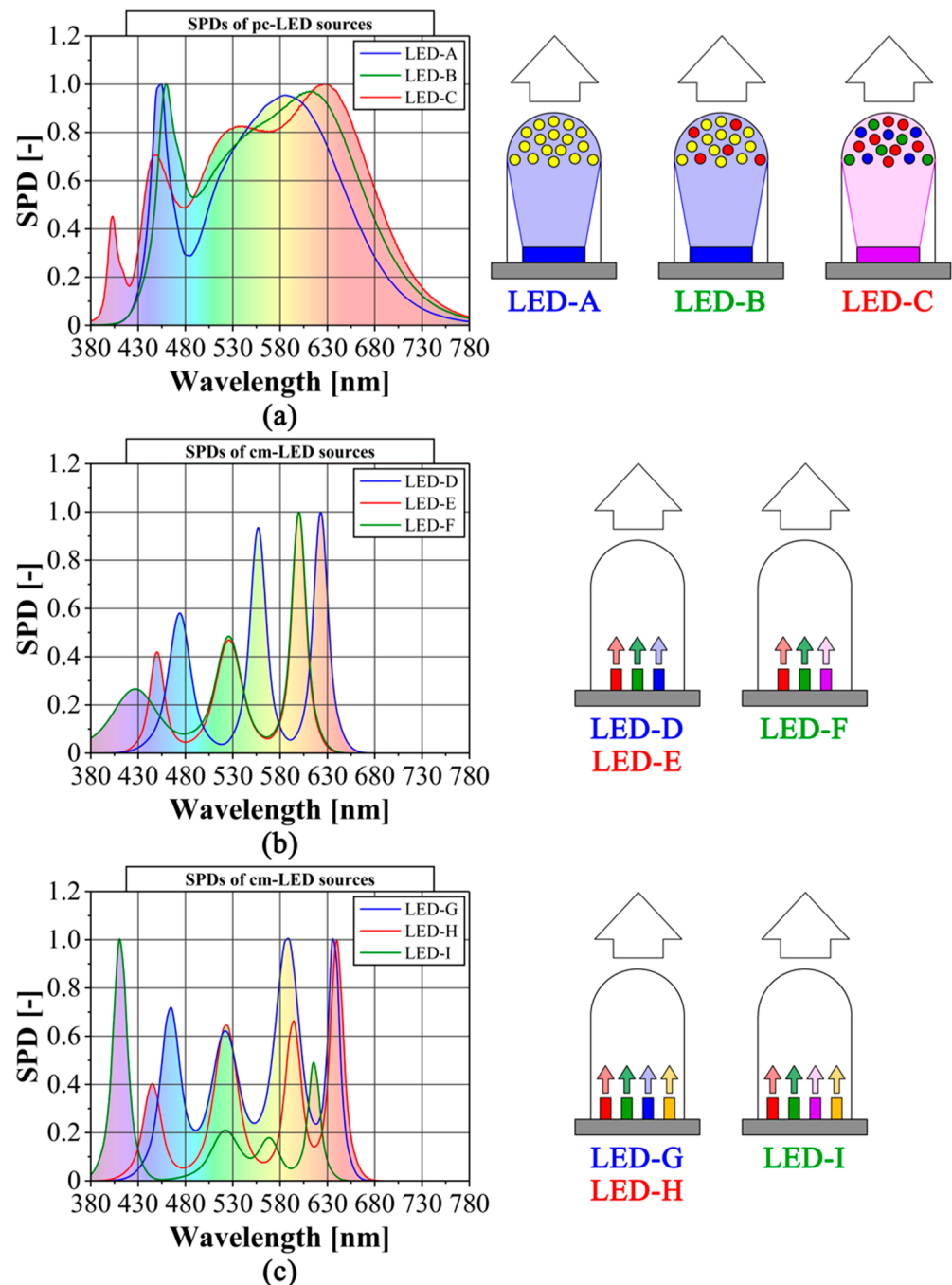


Figure 2. The relative SPDs of (a) white pc-LEDs, (b) RGB cm-LEDs, and (c) RGBA cm-LEDs.

Table 1. Life time and luminous efficacy of fluorescent lamps and LEDs [54–57].

Light Source	Luminous Efficacy of Source (LES) [lm/W]	Luminous Efficiency of Radiation (LER) [lm/W]	Lifetime [10 ³ h]	Mercury (Hg) Content
Fluorescent lamps (FL)	40–100	290–347	6–20	YES
LED	58–173	248–409	20–50	NO

The normative recommendations for lighting design are mainly based on photometric parameters like illuminance and luminance [58–62]. When fluorescent lighting was dominating the market, the color quality of light sources was described using only CCT [31,45] and CRI Ra [63]. However, the CCT does not provide a comprehensive characterization of the emitted LED light, as has been proven and described in detail in the scientific literature [64–66]. Research has firmly demonstrated that Ra is not consistently correlated with the visual assessment of color quality. Additionally, CRI Ra does not fully reflect the color quality perceived by users [67–70]. The potential for using LED technology as a replacement for traditional lighting devices has been extensively investigated by researchers, with findings presented in numerous research papers. Given the scientific and practical importance of this topic (especially given the fact that there are some general lighting users [71] who like to have the same lighting comfort as when FL lamps are applied [72–74]), there is a substantial body of published research on it.

To conduct a systematic review of the literature, the PRISMA 2020 protocol (a widely recognized method for preparing systematic reviews [75–77]) was used. The PRISMA 2020 collects and synthesizes available scientific evidence on a specific, clearly defined research topic [19,78–80]. Our literature review (see details in Appendix A) on lighting retrofitting by LEDs is based on scientific articles indexed in the Scopus and Web of Science databases, which are internationally recognized as comprehensive sources of scientific literature from reputable journals [81,82]. Scopus has been indexing publications since 1823, but the current system was created and launched in 2004. The Web of Science database contains retrospective data, including publications dating back to 1900, making it an invaluable resource for researchers. We created an original dataset comprising scientific works on the subject of selecting LED substitutes for previously used FL sources. We followed the following criteria for our dataset:

- There was no time frame set for published scientific papers.
- If the paper was in a language other than English, we included it if it had an official English abstract.
- The papers must be available to obtain from a library, scientific databases, or from the authors by request.

The resulting set of literature was imported into the SciSpace Premium version of literature review software [83], which enables comprehensive and optimal performance of literature reviews.

Figure 3 presents a “step by step” chart of systematic literature review by the PRISMA 2020 method. The review encompassed papers (see Appendix A) that describe methods of selecting LED retrofitting solutions, taking into account the user’s preferences regarding the quality of lighting while optimizing electricity consumption for lighting purposes. A total of 5943 records on the topic of LED retrofitting were identified in the WoS database, while 2671 records were available in the Scopus database. Following the removal of duplicates, the total number of records was 7587. The identified records served as the starting point for the subsequent phase of the review, which entailed locating results that explicitly address the transition from fluorescent lighting (FL) to LED technology and its associated

implications for energy usage reduction and user preference criteria. This yielded a total of 1024 papers from the WoS database and 707 papers from the Scopus database.

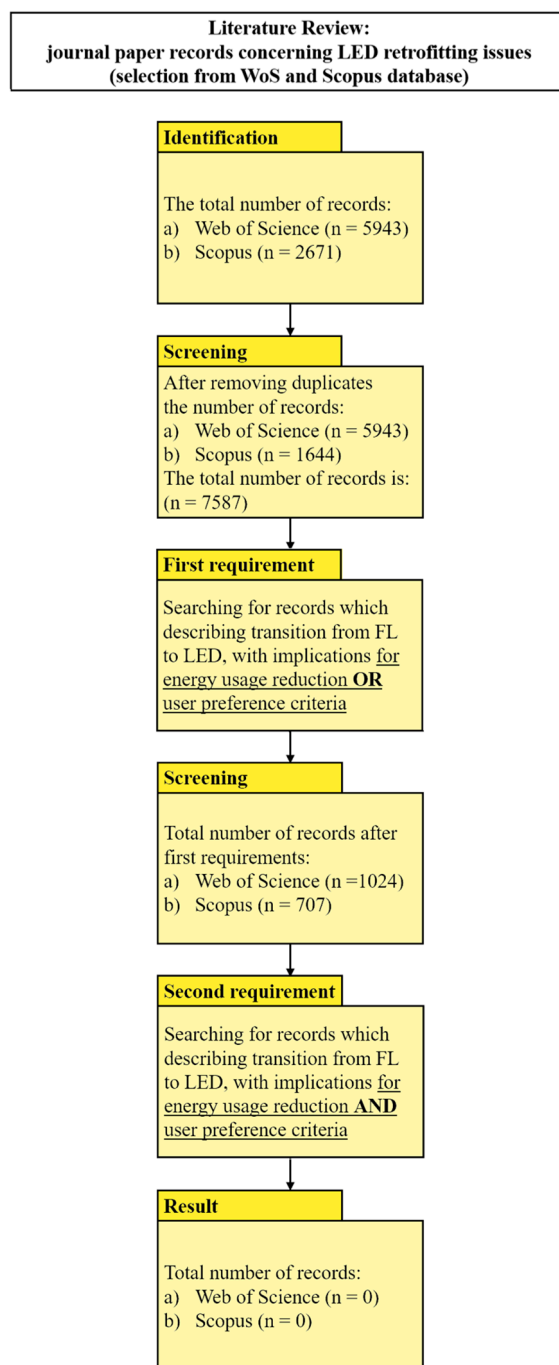


Figure 3. Diagram of the PRISMA 2020 system used to develop the literature review on lighting retrofitting by LEDs.

After examining the content of these selected articles, it was determined that studies conducted globally have demonstrated that the transition from fluorescent to LED lighting, focused on energy efficiency [84–87] with lighting parameters maintained at comparable levels [88,89], has not always been met with positive judgment [88,90–92] on the lighting quality by users. Even when white LED light is of identical chromaticity, it can appear markedly different when judged by different observers [45,93,94], which means that user preferences are impacted significantly by the perceived lighting quality. This discrepancy

can be attributed to differences in SPD, such as variations in the blue peak wavelength of the light in examination, which can influence the perceived color of white light [95–97]. However, when the search was conducted for records that describe both “energy usage reduction” and “user preference” phrases, no records were identified.

The findings of this study highlight a notable research gap in this field, as no papers were identified that addressed this subject. This indicates the need for further research on this subject, given the intrinsic interest and potential applicability to a range of fields. This is particularly pertinent in the current era, when the rational reduction of energy consumption without degrading the quality is a designer’s priority.

2. Materials and Methods

In the process of replacing fluorescent lighting with LED products, it is important to maintain a comparable level of color rendering quality to avoid user dissatisfaction. The method of assessing the color quality of lighting, known as the color preference criteria (CPC) [98], was introduced by the American National Standard Institute as the IES TM-30-20 standard in 2020. The CPC method is based on colorimetric parameters [65], such as the general color fidelity index (R_f) introduced by CIE in 2017, which is a supplementary parameter to general CRI Ra (which fails to accurately describe the color quality of white LED lights in many cases [99–101]), the color gamut area index (R_g), and local chroma shift ($R_{cs,h1}$) specified by hue angle bin [64,102,103] (see Table 2). The CPC classification system comprises four levels, with classes defined as P1, P2, P3, and out of class.

Table 2. The categorization parameters of the color preference criteria method [65].

Class P1	Class P2	Class P3
“Best”	“Good”	“Acceptable”
$R_g \geq 95$	$R_g \geq 92$	$R_g \geq 89$
$R_f \geq 78$	$R_f \geq 74$	$R_f \geq 70$
$-1\% \leq R_{cs,h1} \leq 15\%$	$-7\% \leq R_{cs,h1} \leq 19\%$	$-12\% \leq R_{cs,h1} \leq 23\%$

The R_f [104] is currently the most accurate standard measure of color fidelity with respect to a reference illuminant. It is a significant improvement over the CRI Ra, which does not correlate well with visual evaluation by general users [105,106]. A higher R_f value indicates a better fidelity in color rendering, meaning that the colors rendered by the light source are closer to their true, natural appearance.

The R_g is a metric that quantifies the average change in chroma across a color gamut relative to a reference illuminant [107]. A higher R_g value indicates that the light source can render a wide range of colors more accurately and vividly, improving the overall visual experience.

The $R_{cs,h1}$ values measure the change in chroma (saturation) of a red hue compared to a reference illuminant [108]. Accurate red rendition is crucial for evaluating how well colors are represented under various lighting conditions [109–111]. A higher $R_{cs,h1}$ value indicates a greater increase in chroma for that particular hue, which can be perceived as more vivid or saturated colors. Conversely, a lower value suggests a decrease in chroma, leading to less vibrant colors.

2.1. Fluorescent Lamps Evaluated in This Study

The nominal CCT of FL (Figure 4) is defined in accordance with the specifications outlined in the ANSI C78.376-2014 standard [112]. This document delineates the tolerances for the chromaticities of FLs for each nominal CCT. In the case of the FL covered by this standard, the chromaticity tolerance is defined by MacAdam ellipses [113,114]. Using a

more restricted categorization, this standard establishes a four-step categorization and a five-step categorization with less restricted requirements [115].

The nominal CCT of LEDs is defined by seven-step quadrangles (Figure 4) in the ANSI C78.377-2017 standard [116].

In addition, to maintain a comparable color-rendering index, CRI Ra is sought when switching from FL to LEDs. However, this approach is frequently inadequate to meet the expectations of users of upgraded lighting systems regarding the color quality of proposed LED replacements for fluorescent lamps. Accordingly, this paper proposes an expansion of these fundamental requirements by incorporating an evaluation of the chromaticity point, with the objective of ensuring the nominal CCT of LEDs also meets the CCT specifications of fluorescent lamps. Ensuring user satisfaction with the color quality of upgraded lighting represents a critical consideration. A methodology based on the user-centered color preference criteria, which serve as a measure of lighting preferences, may prove useful in the selection of LED replacements for fluorescent lamps.

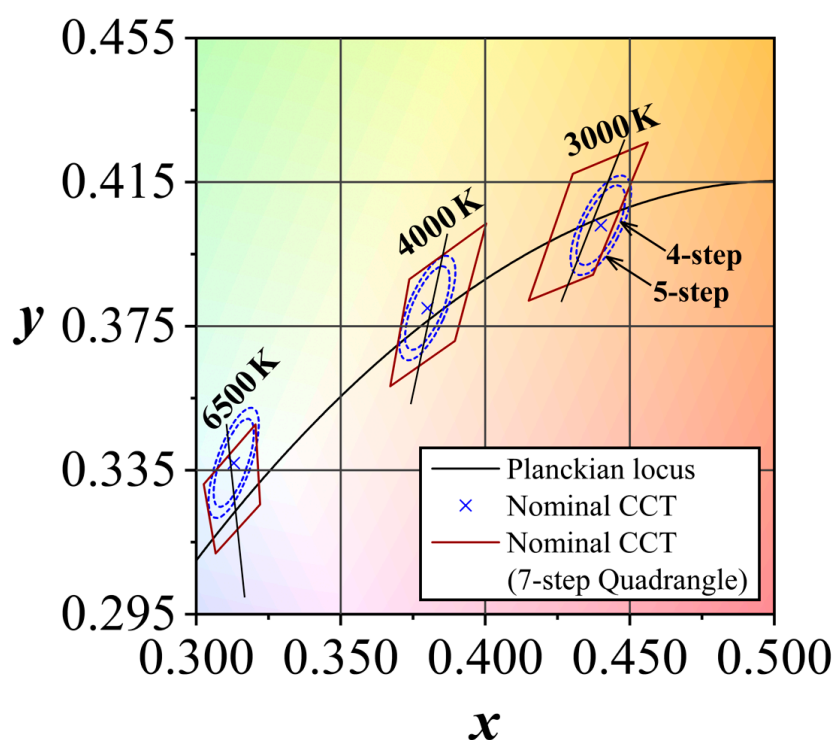


Figure 4. Illustration of nominal CCT tolerances of LEDs given by ANSI seven-step quadrangles and fluorescent lamps (MacAdam ellipses) for 3000, 4000, and 6500 K.

A total of 36 FL sources having different SPDs were considered. The corresponding data were retrieved from an open-source repository of lamp data provided by CIE [31] and the ANSI/IES TM-30 document [65]. The SPDs of FL according to their nominal CCT are illustrated in Figures 5–7 for 3000, 4000, and 6500 K, respectively. The lighting parameters for FL are presented in Table 3. The set of SPDs for FL, presented in Figures 4–6, is representative of the typical FL products used in general lighting, despite the limited number of samples having different parameters. It should be noted that the aforementioned sample numbers are representative of the fluorescent lamps typically used in compliance with the colorimetry standard [31,65]. This is due to the fact that fluorescent lamp technology has been refined and optimized over several decades of mass production [115,117], resulting in products with similar properties. As shown in Figure 5, for a nominal CCT of 3000 K, there are three (3) FLs in the P3 class and five (5) FLs that are out of class. In the case of FL with a nominal CCT of 4000 K (Figure 6), two of them are in the P2 class, six are in the P3 class,

and two are out of the class. With regard to FL with a nominal CCT of 6500 K (Figure 7), one is in the P1 class, two are in the P2 class, four are in the P3 class, and eleven are out of class. Figure 8 presents a graphical illustration of all the analyzed fluorescent sources, categorized according to the CPC methodology.

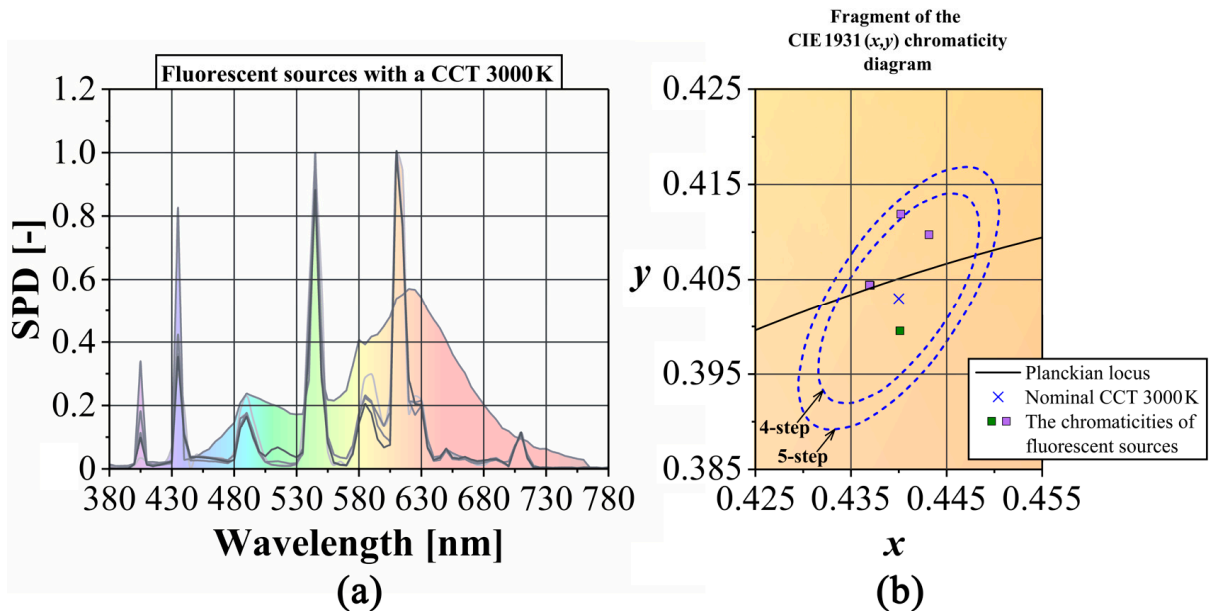


Figure 5. A summary of (a) the relative spectral power distributions (the data were derived from the CIE 015:2018 document [31]) of typical warm white fluorescent lamps (CCT 3000 K), with (b) their chromaticities marked as squares with different colors corresponding to the different classes of color preference: green represents FL belonging to the P2 class, and violet is for the P3 class.

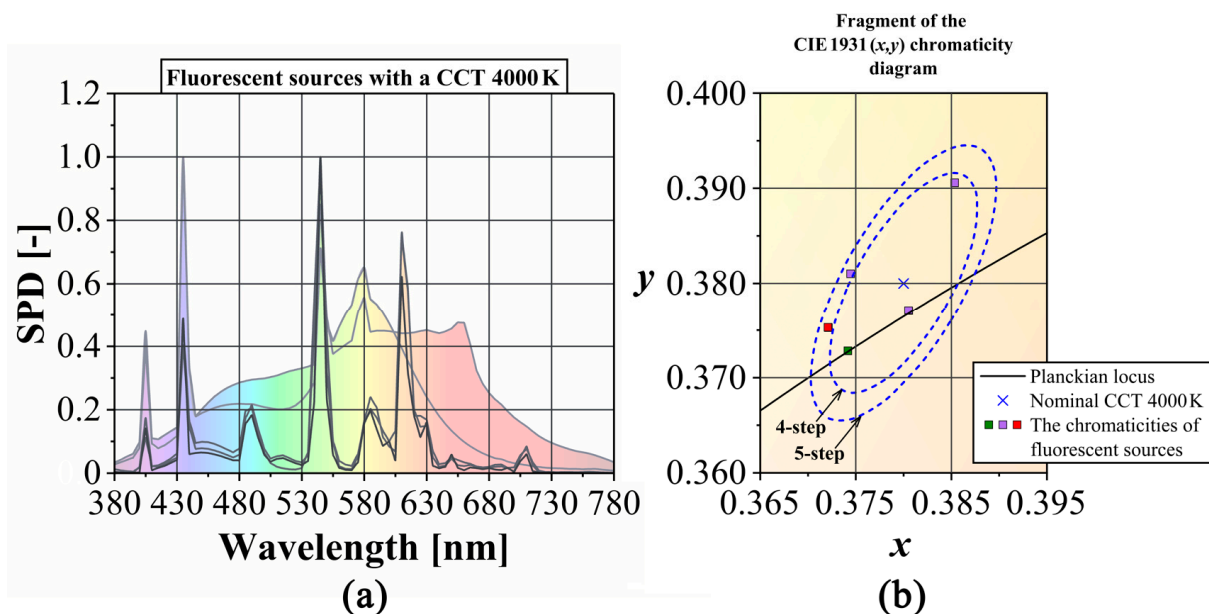


Figure 6. A summary of (a) the relative spectral power distributions (the data were derived from the CIE 015:2018 document [31]) describing typical neutral white fluorescent lamps (CCT 4000 K), with (b) their chromaticities marked as squares with different colors representing the different classes of color preference: green represents FL belonging to the P2 class, violet is for the P3 class, and red stands for out of class.

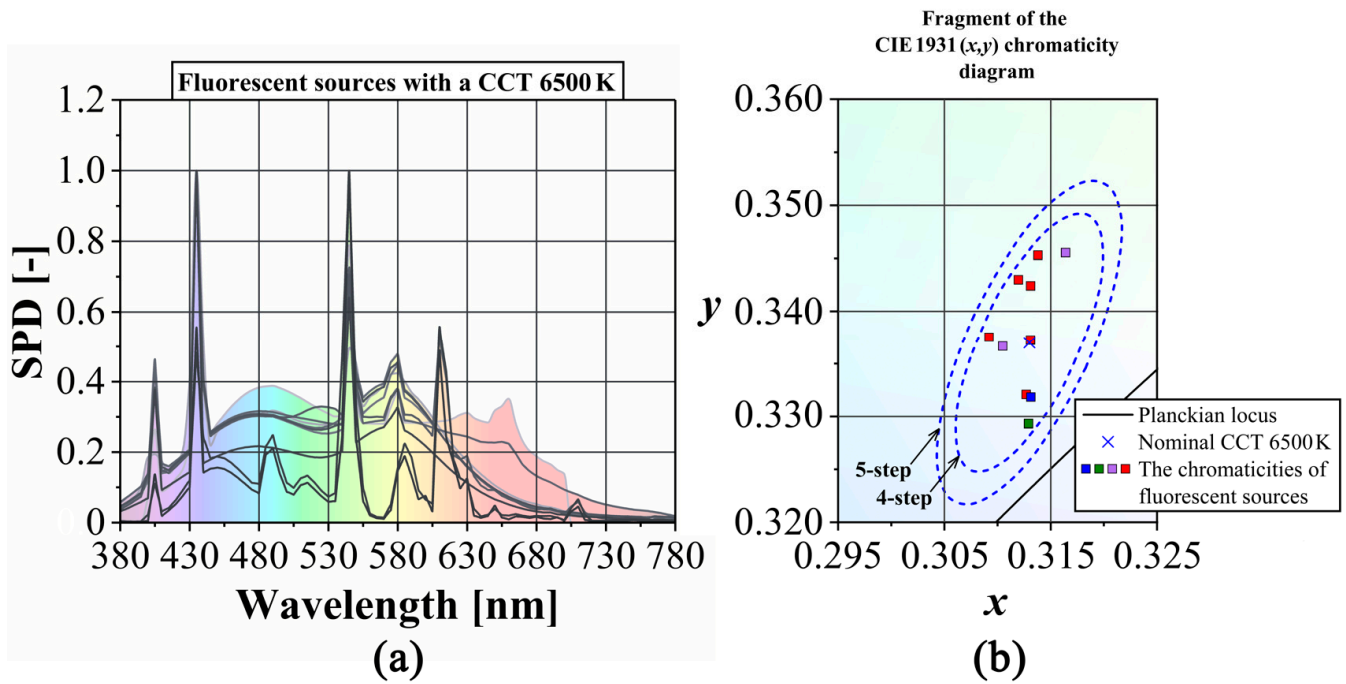


Figure 7. A summary of (a) the relative spectral power distributions (the data were derived from the CIE 015:2018 document [31]) of typical cold white fluorescent lamps (CCT 6500 K), with (b) their chromaticities marked as squares with different colors corresponding to the different classes of color preference: blue represents the P1 class, green represents FL belonging to the P2 class, violet is for the P3 class, and red stands for out of class.

Table 3. The parameters of typical fluorescent sources.

Parameter	3000 K	4000 K	6500 K
Total [pcs.]	8	10	18
CRI [-]	83 ÷ 95	64 ÷ 90	72 ÷ 97
LER [lm/W]	286 ÷ 368	269 ÷ 349	254 ÷ 312
m-DER [-]	0.39 ÷ 0.48	0.55 ÷ 0.66	0.83 ÷ 0.98
R_g	99 ÷ 106	86 ÷ 101	87 ÷ 101
R_f	77 ÷ 90	70 ÷ 91	77 ÷ 98
$R_{cs,h1}$	-9 ÷ -2	-25 ÷ -4	-23 ÷ 1

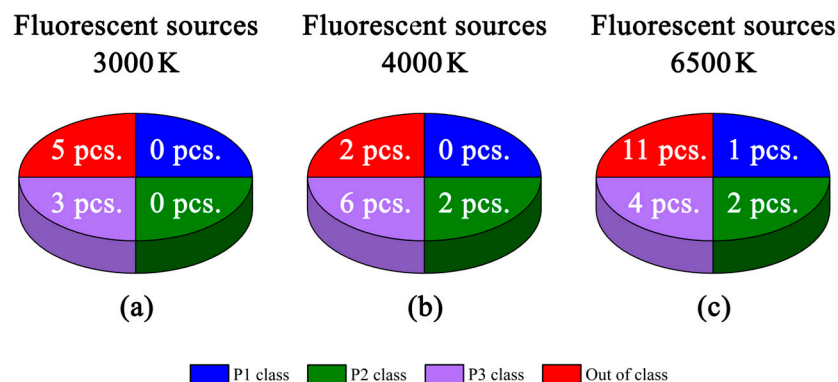


Figure 8. A summary of typical white fluorescent lamps with nominal CCT of (a) 3000 K, (b) 4000 K, and (c) 6500 K. CPC classes are represented with different colors: blue represents the P1 class, green represents FL belonging to the P2 class, violet is for the P3 class, and red stands for out of class.

2.2. LEDs Evaluated in This Study

The SPD data of commercially available LEDs were extracted from publicly available databases: “Real Light Source SPDs and Color Data for Use in Research” [118] and “EM-PIR 15SIB07 PhotoLED—Database of LED product spectra” [119]. LEDs with nominal CCT of 3000 K (582 pcs), 4000 K (344 pcs), and 6500 K (107 pcs) were selected according to the ANSI chromaticity requirements. Their chromaticities are presented in Figure 9 (represented by a gray and yellow color marker). As can be seen in this figure, the LEDs considered as replacements of FLs must align with the ANSI quadrangles’ nominal CCT and fall within the five-step ellipse color tolerance for fluorescent lamps (yellow markers). The SPDs of LEDs with chromaticities represented by yellow markers are provided in Figure 10, Figure 13 and Figure 16 for nominal CCT values of 3000 K (310 pcs), 4000 K (267 pcs), and 6500 K (49 pcs), respectively. The number of light-emitting diodes (LEDs) with CCT values of 3000 and 4000 K is comparable. The number of LEDs with a CCT of 6500 K is considerably smaller, which is attributable to the fact that they are not as prevalent in general lighting as natural and warm LEDs. Their relatively low popularity can be attributed to the fact that their spectrum contains a greater proportion of blue light, which can result in eye fatigue, particularly when exposure is prolonged, and can also lead to accelerated deterioration of the materials used in LEDs, such as phosphor, which affects changes in the spectral distribution during use.

The values of metrics that are used in the CPC methodology are illustrated in polar diagrams in Figure 11, Figure 14 and Figure 17 for LED replacements of FLs with nominal CCT values of 3000, 4000, and 6500 K, respectively, and the values of metrics are (a) R_g , (b) R_f , and (c) $R_{cs,h1}$, respectively. The LED replacements of FLs are marked as circles with different colors for the different color preference criteria class: blue represents the P1 class, green represents FLs belonging to the P2 class, violet is for the P3 class, and red stands for out of class. Additionally, these graphs assign the yellow (P1), orange (P2), blue (P3), and white (out of class) colors to areas in order to indicate the required zones for CPC classes P1 (blue circles), P2 (green circles), P3 (violet circles), and out of class (red circles), respectively, for those LEDs.

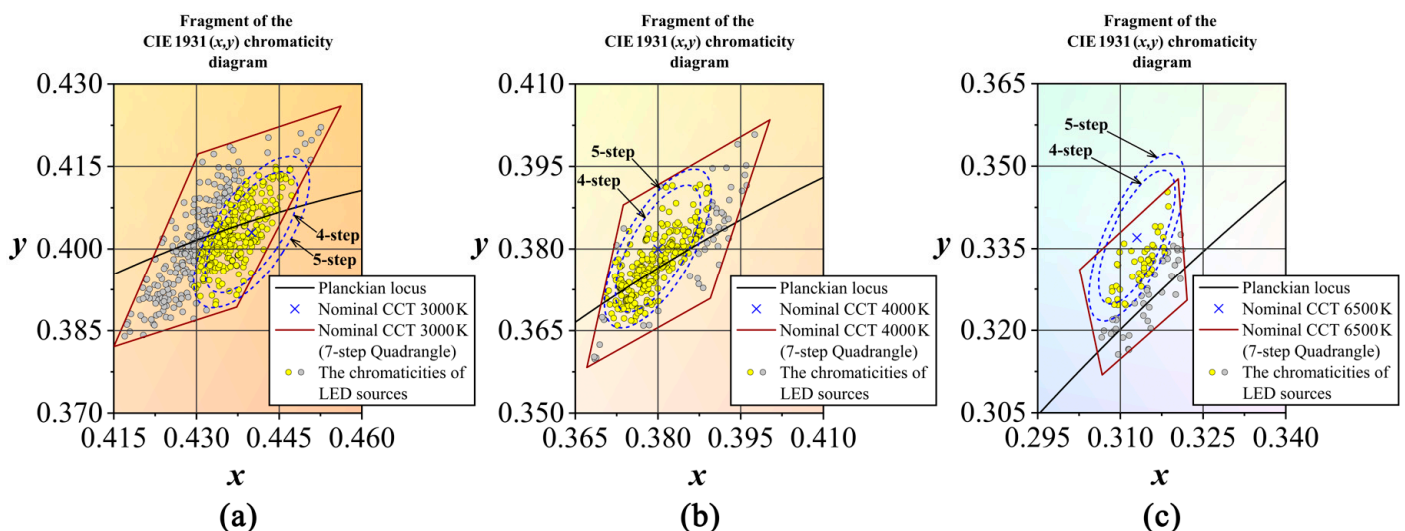


Figure 9. Chromaticity coordinates of LED replacements with nominal CCT values of (a) 3000 K, (b) 4000 K, and (c) 6500 K. LED replacements that align with the ANSI quadrangles’ nominal CCT are represented by a gray color, while yellow markers indicate LED replacements whose chromaticities fall within the ANSI quadrangles and the five-step ellipse color tolerance for fluorescent lamps.

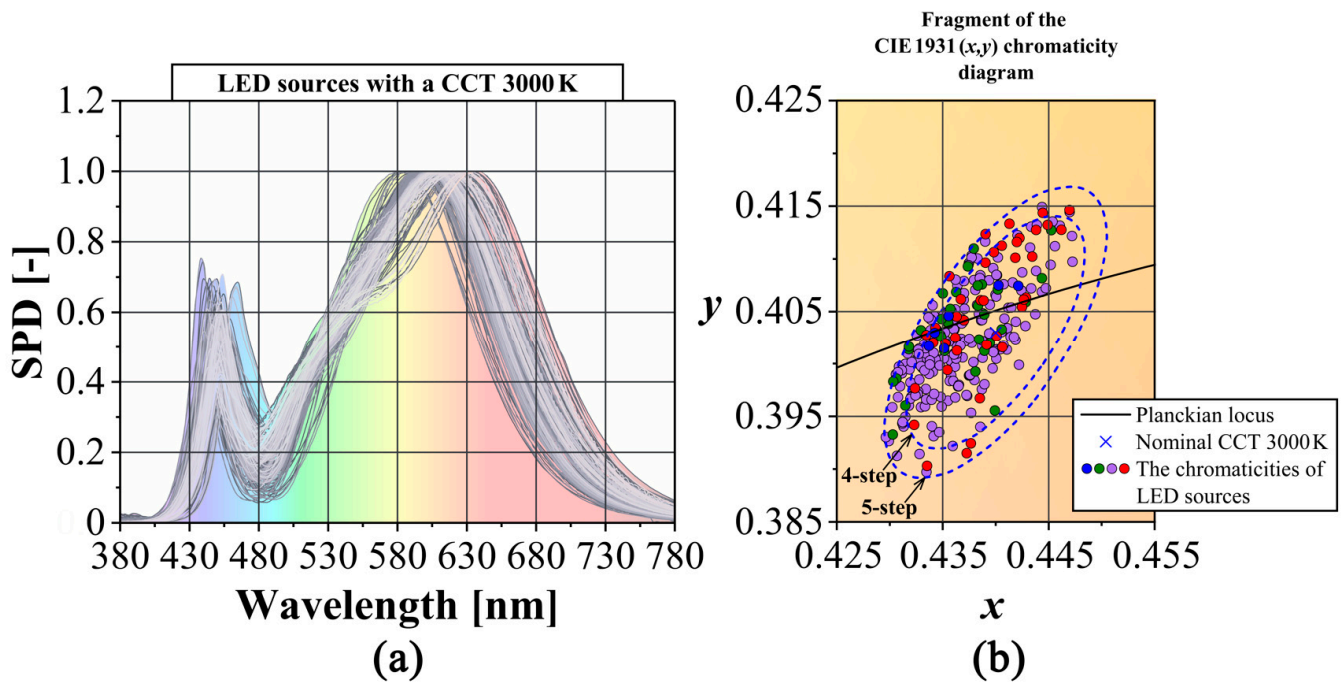


Figure 10. (a) The spectral power distributions and (b) chromaticity coordinates in the CIE 1931 chromaticity diagram of 3000 K LED replacements of FLs.

The values of the other metrics of interest are illustrated in polar diagrams in Figure 12, Figure 15 and Figure 18 for LED replacements with nominal CCT values of 3000, 4000, and 6500 K, and the values of metrics are (a) LER, (b) CRI, and (c) m-DER, respectively. The LED replacements of FLs are marked as circles, with different colors for different color preference criteria classes: blue represents the P1 class, green represents the P2 class, violet is for the P3 class, and red stands for out of class. Figure 19 presents a graph of all the analyzed LED replacements for fluorescent sources, categorized according to the CPC methodology.

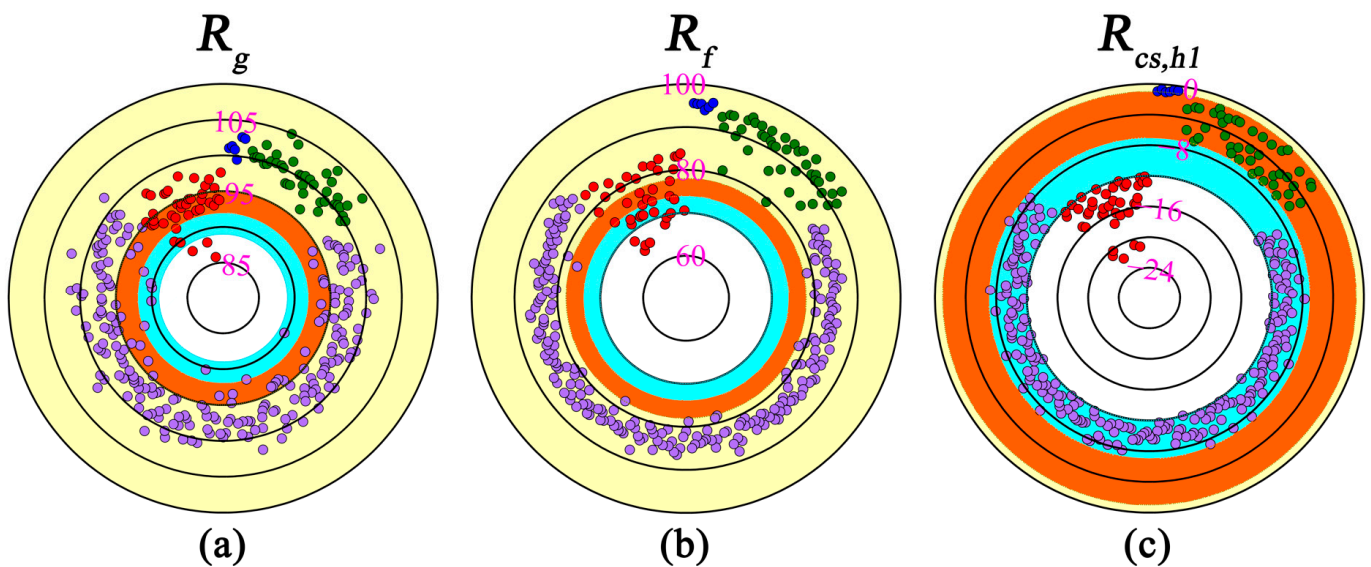


Figure 11. CPC classification parameters for 3000 K LED replacements. (a) R_g , (b) R_f , and (c) $R_{cs,h1}$. Yellow, orange, blue, and white areas indicate required zones for CPC classes P1, P2, P3, and out of class, respectively, for those LEDs.

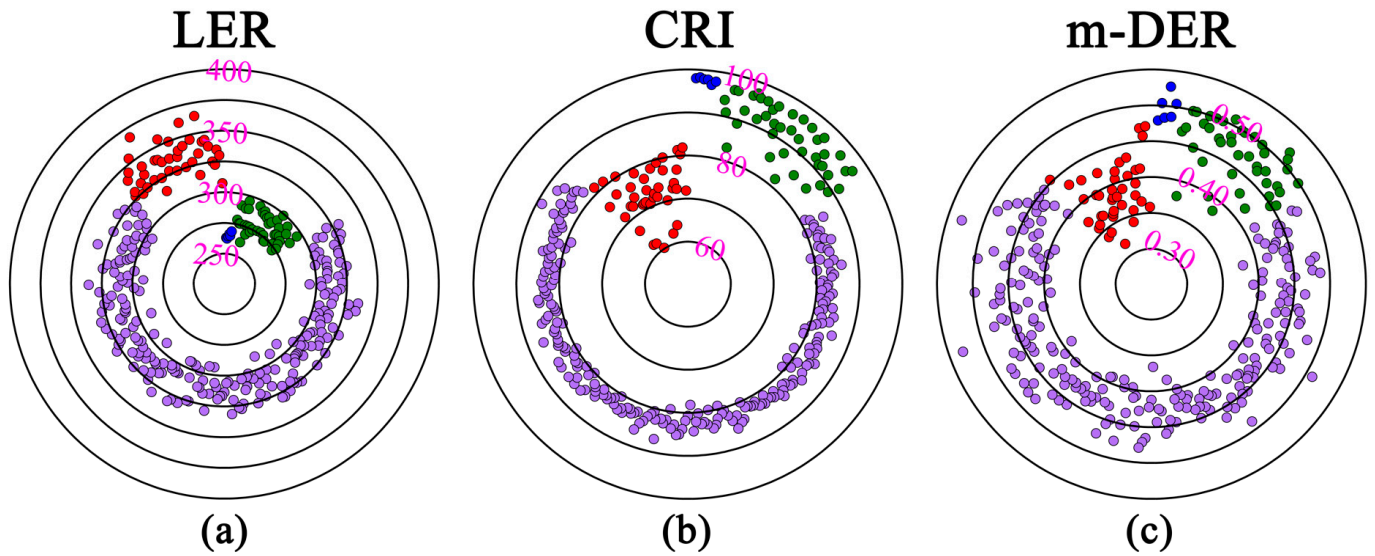


Figure 12. Illustration of the different parameters of interest. (a) LER, (b) CRI, and (c) m-DER of 3000 K LED replacements.

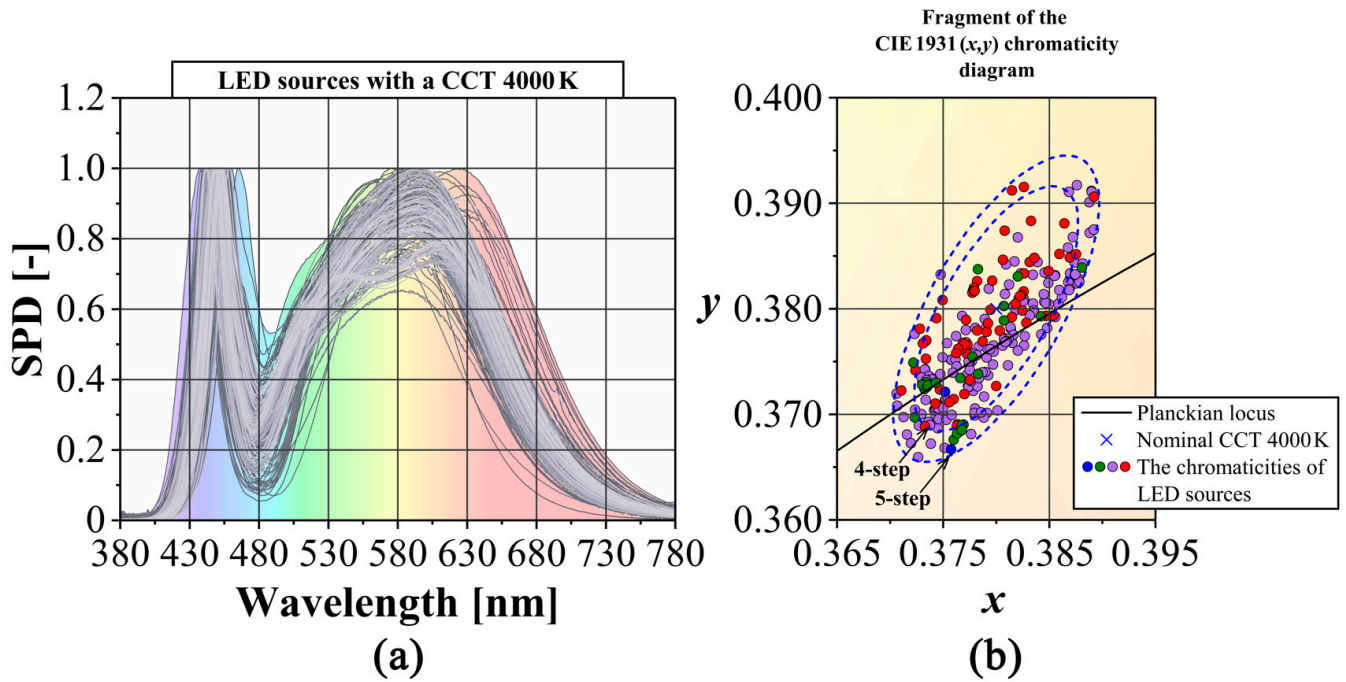


Figure 13. (a) The spectral power distributions and (b) chromaticity coordinates in the CIE 1931 chromaticity diagram of 4000 K LED replacements.

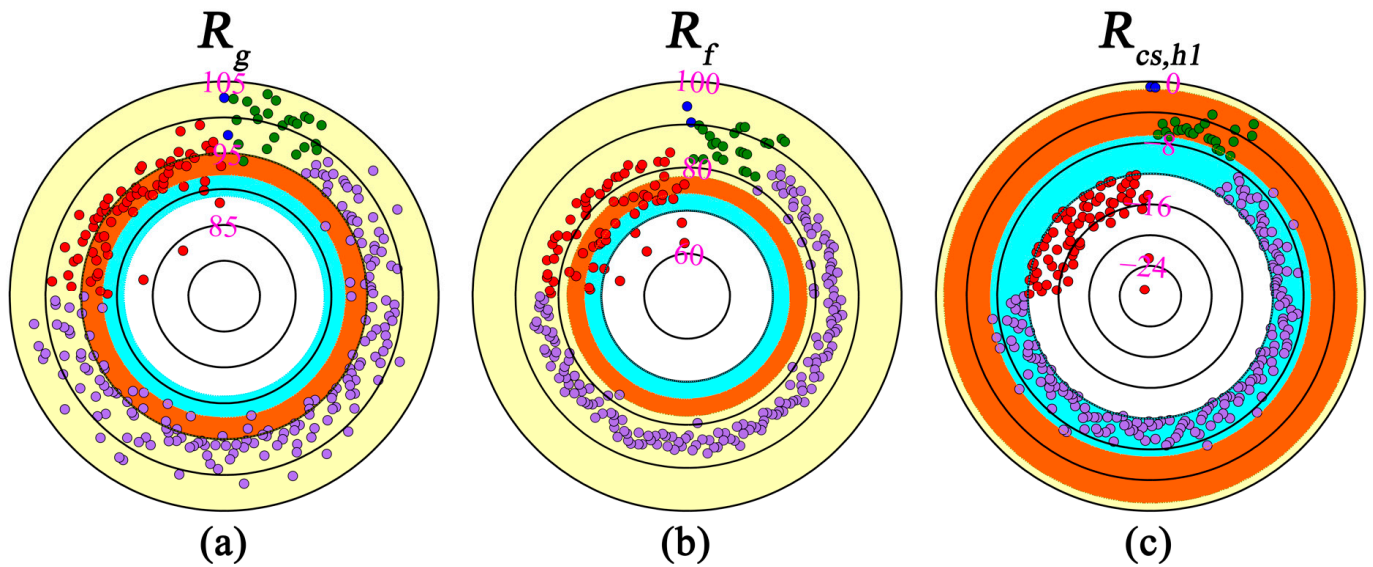


Figure 14. CPC classification parameters for 4000 K LED replacements. (a) R_g , (b) R_f , and (c) $R_{cs,h1}$. Yellow, orange, blue, and white areas indicate the required zones for the CPC classes P1, P2, P3, and out of class, respectively, for those LEDs.

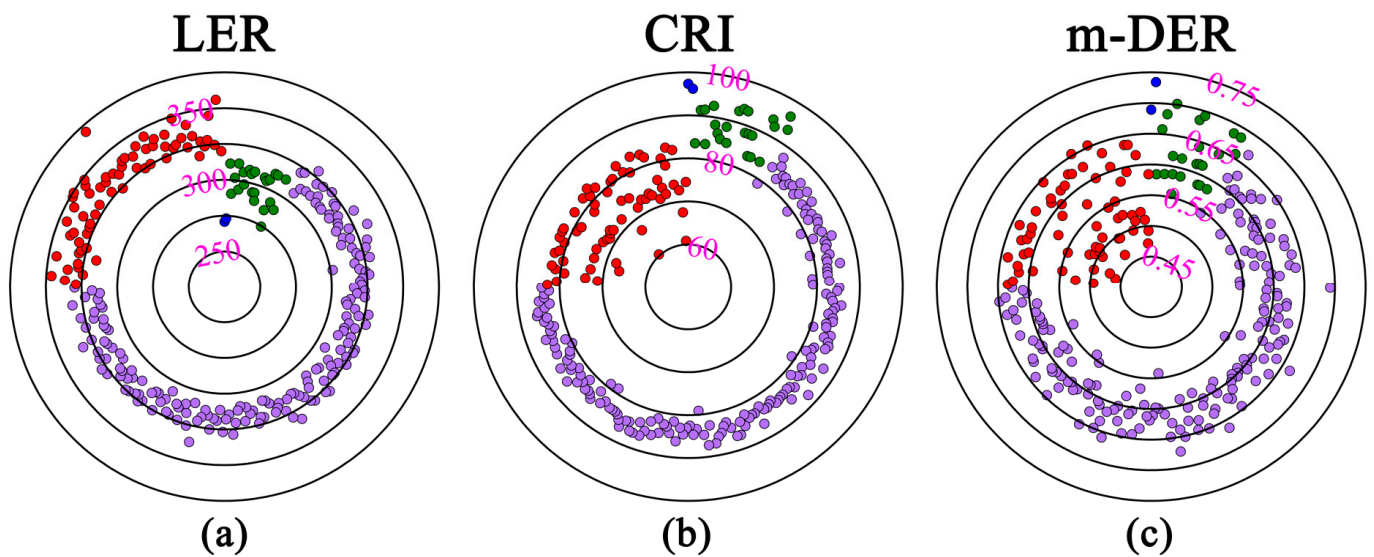


Figure 15. Illustration of the parameters of interest. (a) LER, (b) CRI, and (c) m-DER of 4000 K LED replacements.

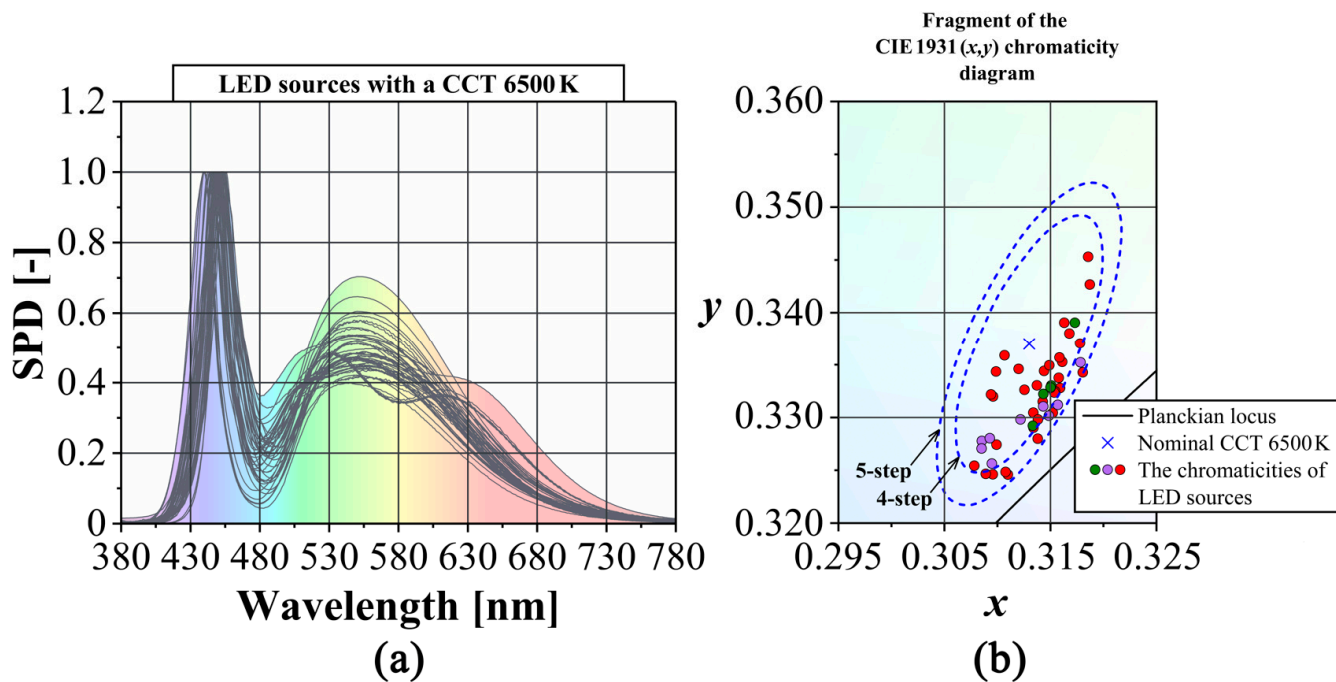


Figure 16. (a) The spectral power distributions and (b) chromaticity coordinates in the CIE 1931 chromaticity diagram of 6500 K LED replacements.

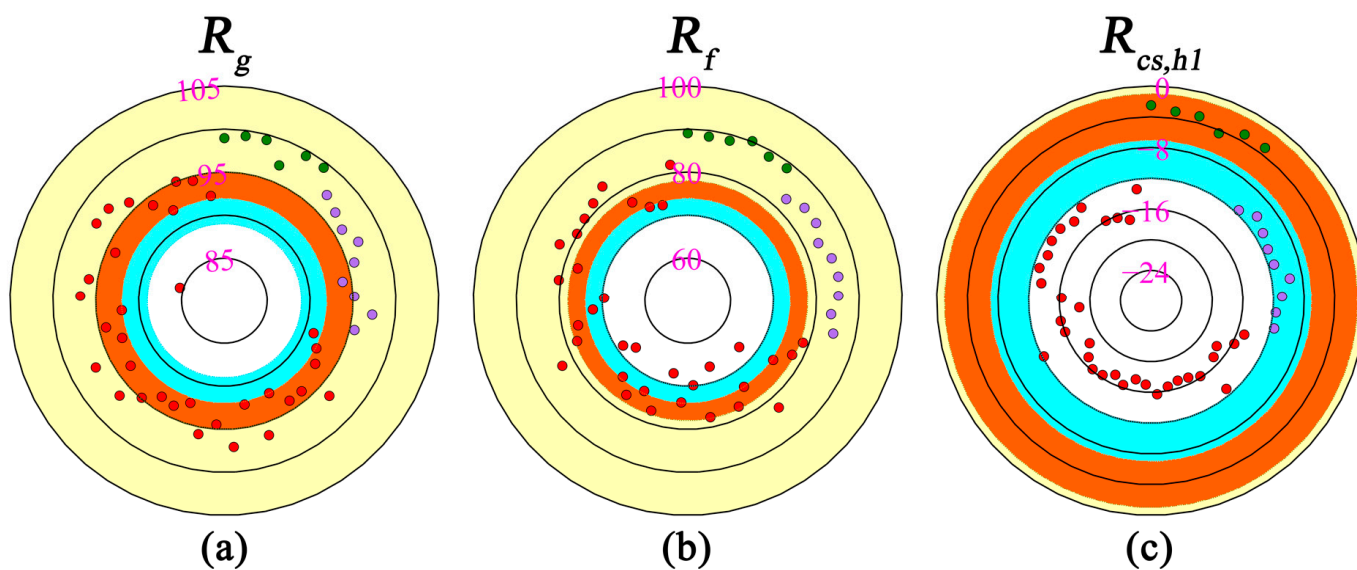


Figure 17. CPC classification parameters for 6500 K LED replacements. (a) R_g , (b) R_f , and (c) $R_{cs,h1}$. Yellow, orange, blue, and white areas indicate the required zones for the CPC classes P1, P2, P3, and out of class, respectively, for those LEDs.

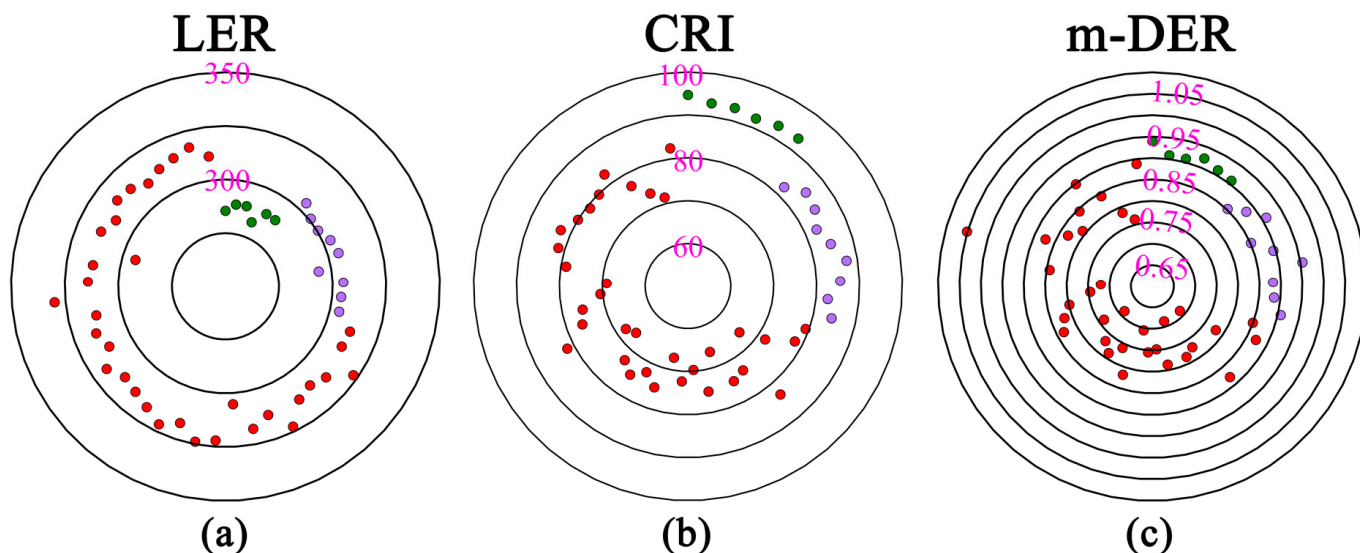


Figure 18. Illustration of the parameters of interest. (a) LER (b) CRI (c) m-DER of 6500 K LED replacements.

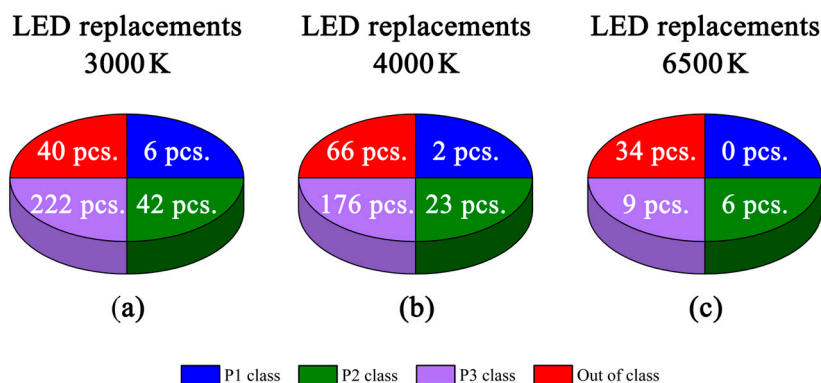


Figure 19. A summary of typical LEDs with nominal CCT of (a) 3000 K, (b) 4000 K, and (c) 6500 K, with CPC classes represented with different colors: blue represents the P1 class, green represents the P2 class, violet is for the P3 class, and red stands for out of class.

3. Results and Discussion

Tables 4–6 present the values of a series of metrics of interest, including LER, CRI, m-DER, R_f , R_g , and $R_{cs,h1}$ parameters with respect to P1, P2, P3, and out of class CPC specifications of typical white fluorescent lamps with nominal CCT values of 3000, 4000, and 6500 K, respectively.

Table 4. FL 3000 K parameters per CPC class.

CPC [-]	LER [lm/W]	CRI [-]	m-DER [-]	R_g [-]	R_f [-]	$R_{cs,h1}$ [%]
P1	-	-	-	-	-	-
P2	285 ÷ 346	86 ÷ 95	0.43 ÷ 0.48	102 ÷ 106	81 ÷ 90	-4.0 ÷ -2.6
P3	353 ÷ 368	83 ÷ 85	0.39 ÷ 0.42	100 ÷ 102	77 ÷ 82	-9.0 ÷ -8.0
Out of class	-	-	-	-	-	-

Table 5. FL 4000 K parameters per CPC class.

CPC [-]	LER [lm/W]	CRI [-]	m-DER [-]	R_g [-]	R_f [-]	$R_{cs,h1}$ [%]
P1	-	-	-	-	-	-
P2	269	90	0.66	100	91	-4.3
P3	337 ÷ 349	83 ÷ 85	0.56 ÷ 0.59	100 ÷ 101	80 ÷ 84	-9.0 ÷ -8.0
Out of class	337	64	0.57	86	70	-24.9

Table 6. FL 6500 K parameters per CPC class.

CPC [-]	LER [lm/W]	CRI [-]	m-DER [-]	R_g [-]	R_f [-]	$R_{cs,h1}$ [%]
P1	263	97	0.98	101	98	1.1
P2	254	90	0.92	99	92	-5.3
P3	306 ÷ 312	84 ÷ 85	0.84 ÷ 0.86	100	85 ÷ 86	-8.3 ÷ -8.2
Out of class	291 ÷ 301	72 ÷ 82	0.84 ÷ 0.88	87 ÷ 94	78 ÷ 86	-23 ÷ -15

Figure 20 presents box plots with values of LER for LED replacements, sorted vertically by CPC preference classes and horizontally by nominal CCT values of 3000, 4000, and 6500 K. Such a data visualization clearly indicates that the mean (marked as a black cross) value of LER increases in value when CPC class decreases (corresponding to a better color preference). This trend is clearly visible for all nominal CCT values. In Figures 21 and 22, the same data visualization is used for the CRI Ra and m-DER metrics. These figures reveal that the mean values of CRI Ra and m-DER decrease when the CPC preference criteria class decreases.

The proposed detailed procedure for selecting high-quality, energy-efficient LED retrofits in modernized buildings:

1. Information regarding the nominal CCT value of FL lamps currently in use in modernized lighting installations is derived, and then four-step and five-step MacAdam ellipses are plotted (based on the ANSI C78.376 [112] and IEC 60081 [115] document regulations).
2. The seven-step quadrangle (according to the ANSI C78.377 document [116]) is used to determine the chromaticities of retrofitting LEDs with the same CCT as FL lamps. Their chromaticities must be located in the intersection of MacAdams ellipses and the seven-step quadrangle.

Due to contemporary lighting regulation, this moment is treated as the end of the procedure, but from the energy efficiency and color lighting quality viewpoints, this can be the starting point of the new detailed procedure that guarantees high-quality and energy-efficient LED retrofits.

3. For LEDs having chromaticities located in the intersection determined by the method from [65] (p. 2), they are evaluated by user-centric lighting quality parameters (m-DER value and color preference criteria method [65] classes P1, P2, P3 based on R_g , R_f , and $R_{cs,h1}$ parameters).
4. The best LED retrofit must balance energy efficiency and user-centric lighting quality.

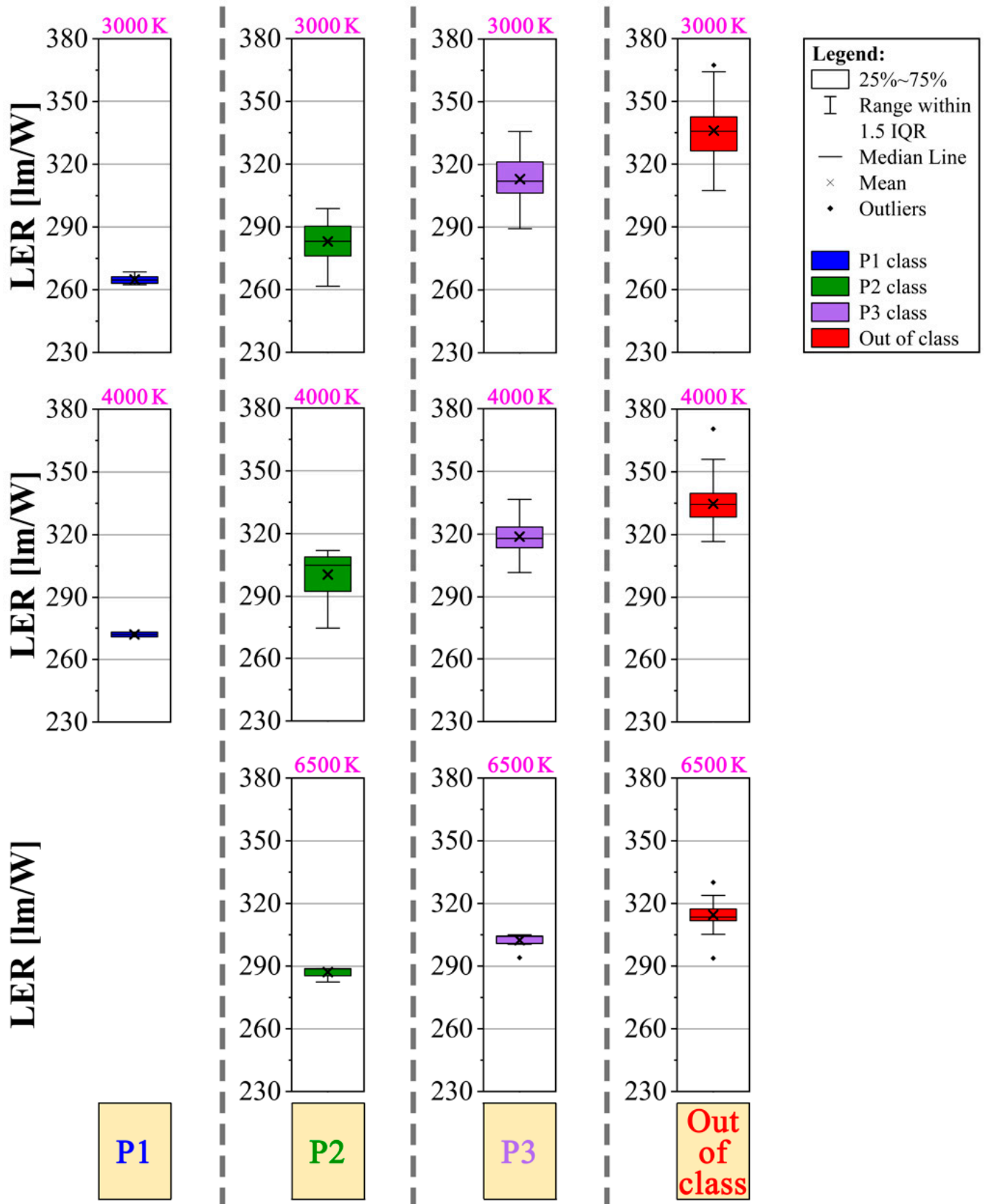


Figure 20. Box plots of the LER metric for LED replacements are aligned horizontally according to the CCT values of 3000, 4000, and 6500 K. The vertical alignment represents the classifications P1, P2, P3, and out of class.

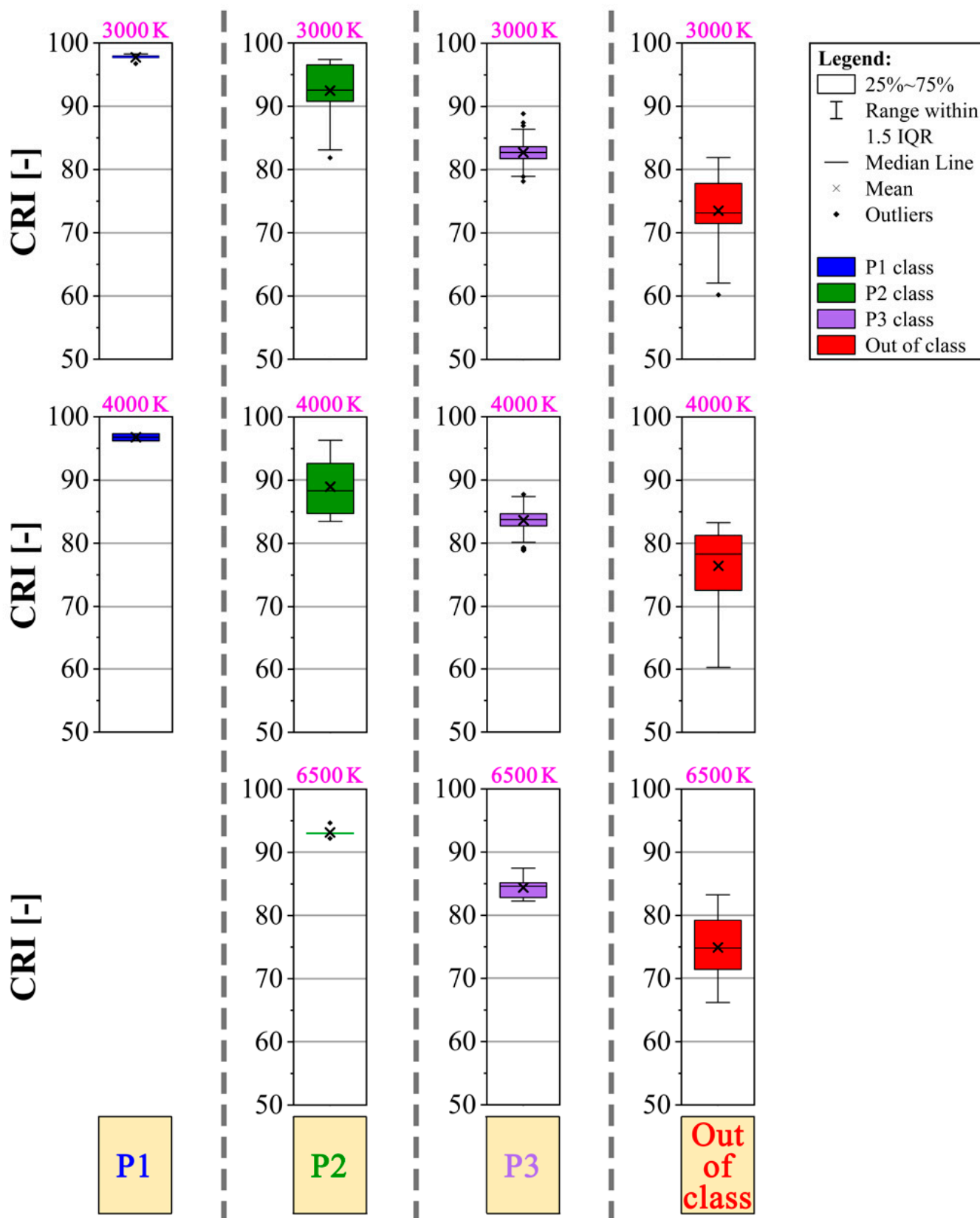


Figure 21. The box plots of the CRI metric for LED replacements are aligned horizontally according to CCT values of 3000, 4000, and 6500 K. The vertical alignment represents the CPC classifications P1, P2, P3, and out of class.

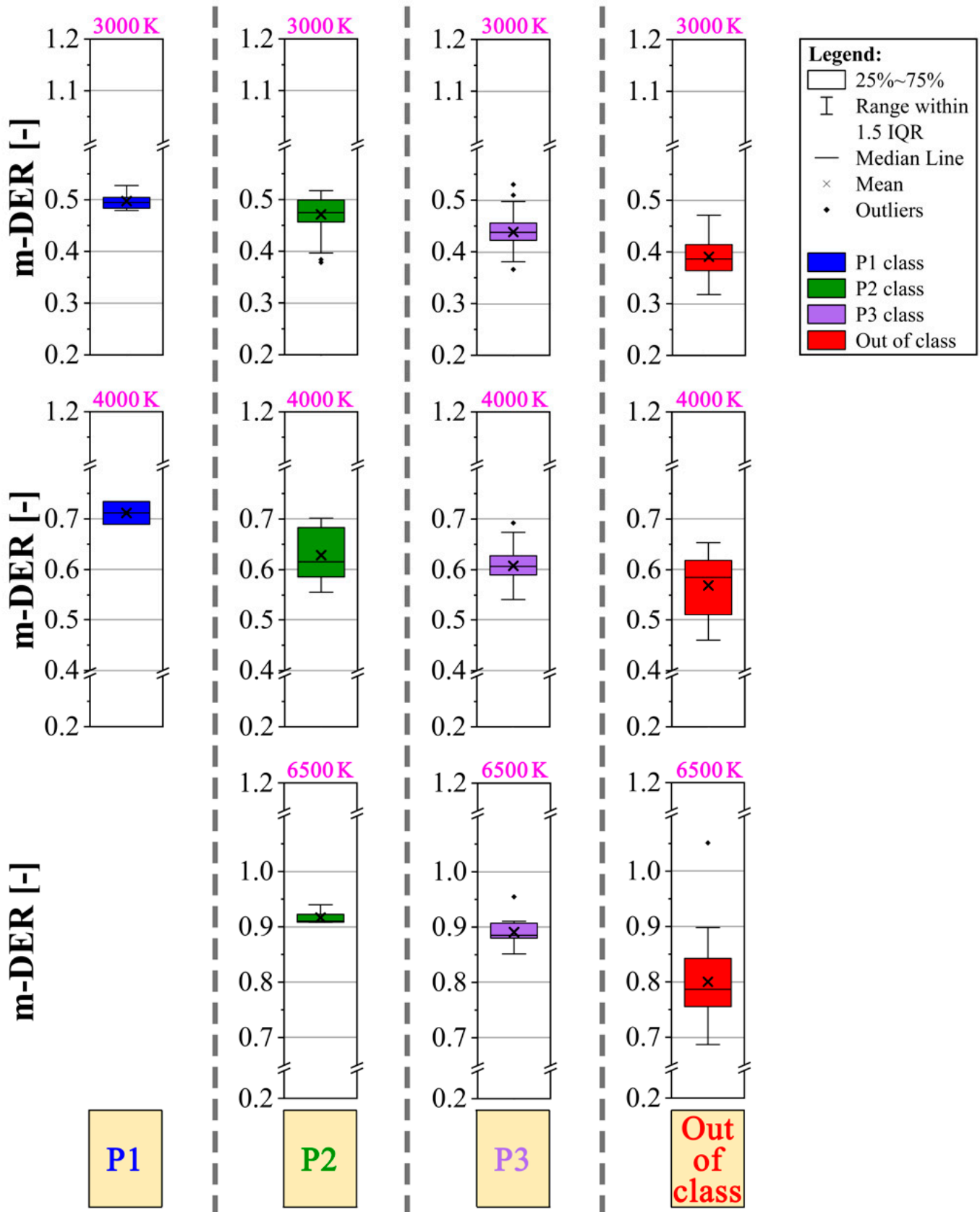


Figure 22. The box plots of the m-DER metric for LED replacements are aligned horizontally according to the CCT values of 3000, 4000, and 6500 K. The vertical alignment represents the CPC classifications P1, P2, P3, and out of class.

4. Conclusions

This study carried out a literature search and selection in accordance with the PRISMA 2020 protocol to conduct a complete review of the literature, minimizing the risk of missing important publications. This protocol provides detailed guidelines on searching databases and other sources of information. The use of PRISMA 2020 revealed a significant research gap in the field of LED retrofits. There is a lack of publications indicating the relationship between energy consumption and user preferences concerning the quality of lighting.

This study demonstrates that lighting installations that have undergone a transition from FL to LED technology perform very differently in terms of energy efficiency, color rendering qualities, and melanopic daylight efficacy ratio. For example, LED replacements with the best color rendering properties (P1 class in the CPC classification) correspond to the least energy-efficient light sources.

The results presented here can serve as a useful tool to select LED replacements for FLs by considering specific user preferences in terms of color rendering and melanopic properties. This approach enables customization to achieve a balance between energy-saving and lighting quality parameters.

An extensive set of LED sources with nominal CCT values of 3000, 4000, and 6500 K was assessed. The results demonstrate that it is possible to select LED replacements with color rendering properties equivalent to or superior to those of existing installations based on FL sources.

Despite the inclusion of the two largest commercial databases containing spectral distributions of light sources, our calculations yielded no fluorescent lamps (CCT 3000 K) of class P1 or out of class, nor fluorescent lamps (CCT 4000 K) of class P1, designated according to the CPC criteria. However, LED replacements were found with these requirements. In addition, it was demonstrated that 6500 K fluorescent lamps can be found in each color preference class, which was not achieved with any of the LED sources in our samples. According to the CPC classification, no LED source with a CCT of 6500 K was identified in class P1.

In the P2 class, which represents intermediate color rendering quality, it was possible to find LED replacements that achieved a CRI Ra of 95 (Figure 21) at all the assessed CCT values. Many of the LED replacements were found to reach a CRI Ra equal to or greater than 80 with the tested CCT values of 3000, 4000, and 6500 K.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

PRISMA 2020 methodology

In order to develop a base of publications, it was necessary to establish a set of criteria for defining keywords. This approach enabled the identification of relevant publications within the databases, thereby supporting the investigation of the topic addressed in this paper. The investigation was performed in three steps. A total of 168 keywords were thus defined. To prevent the inadvertent loss of valuable records, differences in the nomenclature

of substitutes in English and American English were taken into account. The initial term pertained to a semiconductor source (LED), the second signified a substitute, the third denoted an FL source, and the fourth indicated that the item in question belonged to the field of lighting. The remaining terms were related to electricity consumption, the selection process based on colorimetric parameters, and user preferences. In order to conduct a comprehensive search of the publication databases, a variety of potential combinations of words were analyzed in order to identify the most appropriate keywords. The publications were then examined based on the keywords, titles, abstracts, and summaries. As the first step, the following keywords were used:

“LED and substitute and fluorescent and lighting”, “LED and substitute and FL and lighting”, “LED and substitute and CFL and lighting”, “LED and replacement and fluorescent and lighting”, “LED and replacement and FL and lighting”, “LED and replacement and CFL and lighting”, “LED and retrofit and fluorescent and lighting”, “LED and retrofit and FL and lighting”, “LED and retrofit and CFL and lighting”, “Solid-State Lighting and substitute and fluorescent and lighting”, “Solid-State Lighting and substitute and FL and lighting”, “Solid-State Lighting and substitute and CFL and lighting”, “Solid-State Lighting and replacement and fluorescent and lighting”, “Solid-State Lighting and replacement and FL and lighting”, “Solid-State Lighting and replacement and CFL and lighting”, “Solid-State Lighting and retrofit and fluorescent and lighting”, “Solid-State Lighting and retrofit and FL and lighting”, “Solid-State Lighting and retrofit and CFL and lighting”, “Lighting Emitting Diode and substitute and fluorescent and lighting”, “Lighting Emitting Diode and substitute and FL and lighting”, “Lighting Emitting Diode and substitute and CFL and lighting”, “Lighting Emitting Diode and replacement and fluorescent and lighting”, “Lighting Emitting Diode and replacement and FL and lighting”, “Lighting Emitting Diode and replacement and CFL and lighting”, “Lighting Emitting Diode and retrofit and fluorescent and lighting”, “Lighting Emitting Diode and retrofit and FL and lighting”, “Lighting Emitting Diode and retrofit and CFL and lighting”, “LED and fluorescent and lighting”, “LED and FL and lighting”, “LED and CFL and lighting”, “Lighting Emitting Diode and fluorescent and lighting”, “Lighting Emitting Diode and FL and lighting”, “Lighting Emitting Diode and CFL and lighting”, “Solid-State Lighting and fluorescent and lighting”, “Solid-State Lighting and FL and lighting”, “Solid-State Lighting and CFL and lighting”.

In the second step, the developed base of publications was searched to identify results that, in addition to evaluating the suitability of LED substitutes for FL sources, provide insights into the impact of such substitutes on electricity consumption. Furthermore, the selection of substitutes was examined to ascertain colorimetric parameters or the preferences of future users. In this step, the following keywords were applied:

“LED and substitute and fluorescent and lighting and energy”, “LED and substitute and FL and lighting and energy”, “LED and substitute and CFL and lighting and energy”, “LED and replacement and fluorescent and lighting and energy”, “LED and replacement and FL and lighting and energy”, “LED and replacement and CFL and lighting and energy”, “LED and retrofit and fluorescent and lighting and energy”, “LED and retrofit and FL and lighting and energy”, “LED and retrofit and CFL and lighting and energy”, “Solid-State Lighting and substitute and fluorescent and lighting and energy”, “Solid-State Lighting and substitute and FL and lighting and energy”, “Solid-State Lighting and substitute and CFL and lighting and energy”, “Solid-State Lighting and replacement and fluorescent and lighting and energy”, “Solid-State Lighting and replacement and FL and lighting and energy”, “Solid-State Lighting and replacement and CFL and lighting and energy”, “Solid-State Lighting and retrofit and fluorescent and lighting and energy”, “Solid-State Lighting and retrofit and FL and lighting and energy”, “Solid-State Lighting and retrofit and CFL and lighting and energy”, “Lighting Emitting Diode and substitute and fluorescent

Lighting and FL and lighting and preference", "Solid-State Lighting and CFL and lighting and preference", "LED and substitute and fluorescent and lighting and color", "LED and substitute and FL and lighting and color", "LED and substitute and CFL and lighting and color", "LED and replacement and fluorescent and lighting and color", "LED and replacement and FL and lighting and color", "LED and replacement and CFL and lighting and color", "LED and retrofit and fluorescent and lighting and color", "LED and retrofit and FL and lighting and color", "LED and retrofit and CFL and lighting and color", "Solid-State Lighting and substitute and fluorescent and lighting and color", "Solid-State Lighting and substitute and FL and lighting and color", "Solid-State Lighting and substitute and CFL and lighting and color", "Solid-State Lighting and replacement and fluorescent and lighting and color", "Solid-State Lighting and replacement and FL and lighting and color", "Solid-State Lighting and replacement and CFL and lighting and color", "Solid-State Lighting and retrofit and fluorescent and lighting and color", "Solid-State Lighting and retrofit and FL and lighting and color", "Solid-State Lighting and retrofit and CFL and lighting and color", "Lighting Emitting Diode and substitute and fluorescent and lighting and color", "Lighting Emitting Diode and substitute and FL and lighting and color", "Lighting Emitting Diode and substitute and CFL and lighting and color", "Lighting Emitting Diode and replacement and fluorescent and lighting and color", "Lighting Emitting Diode and replacement and FL and lighting and color", "Lighting Emitting Diode and replacement and CFL and lighting and color", "Lighting Emitting Diode and retrofit and fluorescent and lighting and color", "Lighting Emitting Diode and retrofit and FL and lighting and color", "Lighting Emitting Diode and retrofit and CFL and lighting and color", "LED and fluorescent and lighting and color", "LED and FL and lighting and color", "LED and CFL and lighting and color", "Lighting Emitting Diode and fluorescent and lighting and color", "Lighting Emitting Diode and FL and lighting and color", "Lighting Emitting Diode and CFL and lighting and color", "Solid-State Lighting and fluorescent and lighting and color", "Solid-State Lighting and FL and lighting and color", "Solid-State Lighting and CFL and lighting and color".

In the third phase of the study, the database of publications was searched to identify results that indicate that the replacement of fluorescent lighting (FL) sources with light-emitting diodes (LEDs) took into account both the energy aspect and the impact of the replacement on the user and their perception of the replacement. In order to achieve this, the following keywords were entered into the search:

"LED and substitute and fluorescent and lighting and energy and color quality", "LED and substitute and FL and lighting and energy and color quality", "LED and substitute and CFL and lighting and energy and color quality", "LED and replacement and fluorescent and lighting and energy and color quality", "LED and replacement and FL and lighting and energy and color quality", "LED and replacement and CFL and lighting and energy and color quality", "LED and retrofit and fluorescent and lighting and energy and color quality", "LED and retrofit and FL and lighting and energy and color quality", "LED and retrofit and CFL and lighting and energy and color quality", "Solid-State Lighting and substitute and fluorescent and lighting and energy and color quality", "Solid-State Lighting and substitute and FL and lighting and energy and color quality", "Solid-State Lighting and substitute and CFL and lighting and energy and color quality", "Solid-State Lighting and replacement and fluorescent and lighting and energy and color quality", "Solid-State Lighting and replacement and FL and lighting and energy and color quality", "Solid-State Lighting and replacement and CFL and lighting and energy and color quality", "Solid-State Lighting and retrofit and fluorescent and lighting and energy and color quality", "Solid-State Lighting and retrofit and FL and lighting and energy and color quality", "Solid-State Lighting and retrofit and CFL and lighting and energy and color quality", "Lighting Emitting Diode and substitute and fluorescent and lighting and energy and color quality", "Lighting Emitting Diode and substitute and FL and lighting and energy and color quality", "Lighting Emitting Diode and substitute and CFL and lighting and energy and color quality", "Lighting Emitting Diode and replacement and fluorescent and lighting and energy and color quality", "Lighting Emitting Diode and replacement and FL and lighting and energy and color quality", "Lighting Emitting Diode and replacement and CFL and lighting and energy and color quality", "Lighting Emitting Diode and retrofit and fluorescent and lighting and energy and color quality", "Lighting Emitting Diode and retrofit and FL and lighting and energy and color quality", "Lighting Emitting Diode and retrofit and CFL and lighting and energy and color quality".

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