

High-Resolution Spectral Analysis and Luminous Efficiency Evaluation of Various Light Bulbs

George Tai Zhao

The Experimental High School Attached to Beijing Normal University, 14 Erlong Road, Beijing 100032, China

ABSTRACT

Addressing climate change requires lighting technologies that are both energy-efficient and safe for human health. This work systematically evaluates four widely used lighting types—incandescent, halogen, fluorescent, and light-emitting diode (LED) lamps—using a high-resolution spectral observation instrument, which covers the wavelength range of 300–1000 nm with a spectral resolution of 0.45 nm. The spectral measurements are further analyzed to determine the distribution of emitted energy across visible (380–780 nm), ultraviolet (UV, <380 nm), and high-energy blue-light bands (415–455 nm). Results show that incandescent and halogen lamps exhibit low luminous efficacy (~15%) but negligible UV and blue-light emissions. In contrast, fluorescent lamps achieve higher efficacy (92–99%) but emit measurable UV (1–2%) and blue light (4–20%), indicating potential exposure risks. LEDs offer the highest efficacy (~99%) with no detectable UV emission; however, 11–15% of their output falls within the high-energy blue-light range, raising health concerns under prolonged exposure. These findings provide a quantitative basis for designing lighting technologies and standards that integrate both sustainability and health considerations.

Keywords: Luminous efficiency; Spectral analysis; Energy-efficient lighting; LED; Health risk

INTRODUCTION

The energy sector is the largest source of greenhouse gas emissions globally (1). In response to the growing challenge of climate change, countries are accelerating the transition to low-carbon energy systems (2). Improving energy efficiency is a key pathway to reduce emissions, and advances in lighting technologies represent an important component of this effort (3). Globally, lighting electricity consumption constitutes 19% of total electricity use, contributing approximately

1,775 million tons of CO₂ emissions annually (4, 5). To reduce carbon emissions, energy-efficient bulbs such as compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) have been widely adopted (6). New lighting technologies are generally more efficient than traditional ones, significantly lowering energy consumption and reducing greenhouse gas emissions (7). In addition, lighting demand is typically concentrated in the evening, coinciding with peak electricity load; thus, improving lighting efficiency can help alleviate peak demand and facilitate power system optimization. Nevertheless, a wide range of lighting technologies remains available, and their relative energy-saving potentials warrant systematic evaluation.

Ideally, lighting devices should maximize energy within the visible range while minimizing potentially harmful wavelengths, particularly ultraviolet (UV) and high-energy blue light (8). Human eyes can only

Corresponding author: George Tai Zhao, E-mail: tgeorgezhao@gmail.com.

Copyright: © 2026 George Tai Zhao. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Accepted May 11, 2026

<https://doi.org/10.70251/HYJR2348.437885>

perceive spectral energy within the wavelength range of 380–780 nm, and radiation outside this range cannot be captured by human vision. Therefore, if a light source can concentrate most of its energy within the 380–780 nm band, it can achieve high energy efficiency, and such technology is referred to as energy-saving technology. If a light source emits radiation only within this band, it can be considered an ideal light source. However, spectral optimization must also consider health impacts. Short-wavelength UV radiation (<400 nm) is known to pose risks to human health (9) and can also damage paintings and plastic products, so its emission must be minimized or strictly controlled. In addition, excessive exposure to blue light (400–500 nm), particularly within the high-energy blue-light (415–455 nm) bands, has been associated with retinal stress through mechanisms such as oxidative damage and cellular dysfunction (10). These considerations highlight the importance of balancing energy efficiency with spectral safety in lighting spectrum design.

Currently, some studies have attempted to quantify the energy efficiency of different light bulbs. A recent study shows that replacing traditional low-power high-intensity gas discharge bulbs with LED bulbs can yield significant economic benefits (11, 12). Yen *et al.* (11) developed a camera-based intelligent detection method that determines the energy efficiency of bulbs by analyzing the alternating current (AC) signal in their light intensity fluctuations, achieving an accuracy rate of over 95%. Although this method shows high potential, it is sensitive to ambient light in practical applications, requires additional calibration for different types of bulbs, and involves relatively complex computations.

In response to the issues mentioned above, this study employs a high-resolution spectrometer to conduct energy efficiency testing and comparison of different types of light bulbs, providing a scientific method for energy efficiency evaluation. This research not only enables the comparison of energy efficiency across various categories of bulbs but also comprehensively considers their health impacts, offering important insights for consumer choice and industry standard development. The structure of this paper is organized as follows: first, it describes the instruments and equipment used for energy efficiency evaluation, the types of bulbs available on the market, and the proposed method for quantifying energy efficiency; second, it presents the experimental data and comparative analysis; finally, based on these findings, it discusses energy-saving potential, health risks, and propose recommendations.

METHODS AND MATERIALS

Spectral Observation Instrument

To measure the spectral distribution of light bulb radiation, this work employs the Ocean Optics HR-2XR300-5 high-resolution spectrometer (<https://www.oceanoptics.com/spectrometer/hr2/>). This instrument enables precise spectral measurements across the ultraviolet to near-infrared range (300–1000 nm), with a resolution of ~0.45 nm (full width at half maximum), allowing accurate detection of fine spectral features and weak signals. The system incorporates a back-illuminated CCD detector and a symmetric optical design to enhance sensitivity and signal stability. Its fiber-optic input interface and modular configuration support flexible deployment in both laboratory and field settings. In addition, an integrated temperature control system minimizes noise associated with environmental fluctuations, ensuring high measurement stability and reproducibility over extended periods. Throughout the experiment, spectral data for each light bulb were collected 5–10 times. Mean values are reported in each figure, with the minimum–maximum range indicated as the measurement uncertainty.

Four Types of Commercially Available Light Bulbs

This study selects a set of commercially available light bulbs to represent the major lighting technologies currently in use, including light-emitting diode (LED), halogen, incandescent, and fluorescent lamps. In total, six products from different brands are tested, with power ratings ranging from 8 W to 60 W to capture typical household and commercial applications. The samples include two LED bulbs (Xiaoyue 8 W and NVC Lighting 9 W), one halogen bulb (Hexuan Lighting 42 W), one incandescent bulb (Shisheng Lighting 60 W), and two fluorescent bulbs (FSL 8 W and Philips 12 W) (Table 1). This selection provides a representative comparison across lighting technologies, brands, and power levels.

Calculation of energy efficiency and health risks

This section outlines the theoretical framework and methods used to quantify spectral radiance, luminous efficacy, and potential health impacts. In this study, energy efficiency is defined in terms of luminous efficacy, that is, the fraction of emitted energy within the visible wavelength range relative to the total radiative output. For incandescent bulbs, which approximate blackbody radiators, direct measurements are limited to the spectral range of 300–1000 nm. To account for

Table 1. Results of radiation spectrum information of six bulbs in this work. The order of the bulbs is consistent with that in Figure 1.

Number	Brand	Type	Rated Power	Visible Light Ratio (380-780 nm)	UV Light Ratio (<380 nm)	High-energy blue light ratio (415-455 nm)	Energy efficiency	Health Risk
1	Xiaoyue	LED	8W	99.8%	0	11.1%	High	Low overall, but relatively high blue light
2	NVC Lighting	LED	9W	99.9%	0	15.3%		
3	Shisheng Lighting	Incandescent	60W	14.4%	0.23%	0.36%	Low	Very low
4	Hexuan Lighting	Halogen	42W	12.1%	0.15%	0.25%	Low	Very low
5	FSL	Fluorescent	8W	92.6%	1.9%	4.83%	High	Moderate (UV + blue light risks)
6	Philips	Fluorescent	12W	99.2%	1.2%	20.1%		

emission outside this range, the full-spectrum radiative output is estimated by fitting the observed spectrum to the Planck blackbody radiation function. The spectral radiance is thus described as follows:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5 (e^{\frac{hc}{\lambda k_B T}} - 1)}$$

where h is Planck’s constant ($6.626 \times 10^{-34} \text{J s}$), c is the speed of light ($3.0 \times 10^8 \text{m s}^{-1}$), k_B is Boltzmann’s constant ($1.38 \times 10^{-23} \text{J K}^{-1}$), and T is the temperature in Kelvin (K). Based on the blackbody radiation assumption, Equation (1) can be used to estimate the total spectral energy across the full wavelength range.

In spectral analysis, the total radiant energy within a wavelength band $[m, n]$ nm can be obtained by integrating the spectral radiance over that range:

$$F_{band}(T) = \int_m^n I_{\lambda}(T) d\lambda$$

Where $I_{\lambda}(T)$ represents the spectral radiance at wavelength λ and temperature T . When the light source can be treated as a blackbody, $B_{\lambda}(T)$ corresponds to the incident light intensity $I_{\lambda}(T)$. For fluorescent lamps and LEDs, the 300–1000 nm band covers most of their emitted energy. However, for incandescent bulbs, a significant proportion of energy is radiated in the near-infrared and infrared regions. Therefore, this work applies a nonlinear fitting approach based on Planck’s

law to estimate the full-spectrum emitted energy. The specific steps are: (1) determine the optimal temperature parameter via an optimization algorithm so that the theoretical curve of the Planck function in the 300–1000 nm band best fits the measured spectrum; (2) based on this temperature parameter, extrapolate the complete theoretical radiant energy including both visible and infrared wavelengths.

This study further evaluates the biosafety risks of lighting products, focusing on the energy proportions in the ultraviolet (<380 nm) and high-energy blue-light (415–455 nm) bands. Ultraviolet radiation poses hazards to human health (13); the greater the energy in the UV band (<380 nm), the more severe the potential harm to the human body. Beyond harmful UV radiation, visible light at specific wavelengths may also adversely affect health. For example, blue light in the 400–500 nm range presents multidimensional risks to humans; different blue-light wavelengths vary in their impacts on the eyes and circadian rhythm. High-energy blue light (415–455 nm) may cause potential damage to retinal cells, leading to issues such as eye strain and retinal degeneration (14). Accordingly, by quantifying the radiation intensity in the UV band and the energy proportion of high-energy blue light, this work establishes a safety assessment framework for light technologies, providing a scientific basis for health-risk evaluation of different types of lighting products. It is noted that, our results evaluate the potential risk based on spectral composition, rather than direct health outcomes.

RESULTS

Illumination Characteristics of LED Lamps

LEDs operate by injecting an electric current into a compound semiconductor, where electron–hole recombination releases energy in the form of photons, producing illumination (15). The luminous output of an LED generally increases with forward current, while the stability of the drive current directly influences the stability of light emission. In this study, a 220 V constant-voltage AC power supply was used to ensure stable operating conditions. As solid-state “cold” light sources, LEDs exhibit high luminous efficacy, produce relatively little heat, and do not contain hazardous materials such as mercury, all of which contribute to their long operational lifetime.

Spectral analysis of the LED bulbs demonstrates the characteristic high efficiency and favorable safety profiles of modern lighting technologies (Figure 1). For Bulb #1, spectral energy is overwhelmingly concentrated within the 380–780 nm visible range ($\approx 99\%$ of the total energy). It exhibits minor characteristic peaks in the 400–500 nm region and a relatively stable, high-intensity emission across 500–700 nm. Although spectral intensity varies slightly with measurement angle and position, the overall peak structure remains consistent, with emission declining sharply to near zero beyond ~ 750 nm. From a safety perspective, ultraviolet radiation (< 380 nm) is negligible, and the contribution of high-energy blue light (415–455 nm) is modest ($\approx 11\%$), indicating potential health risk.

Similarly, Bulb #2 shows spectral energy primarily

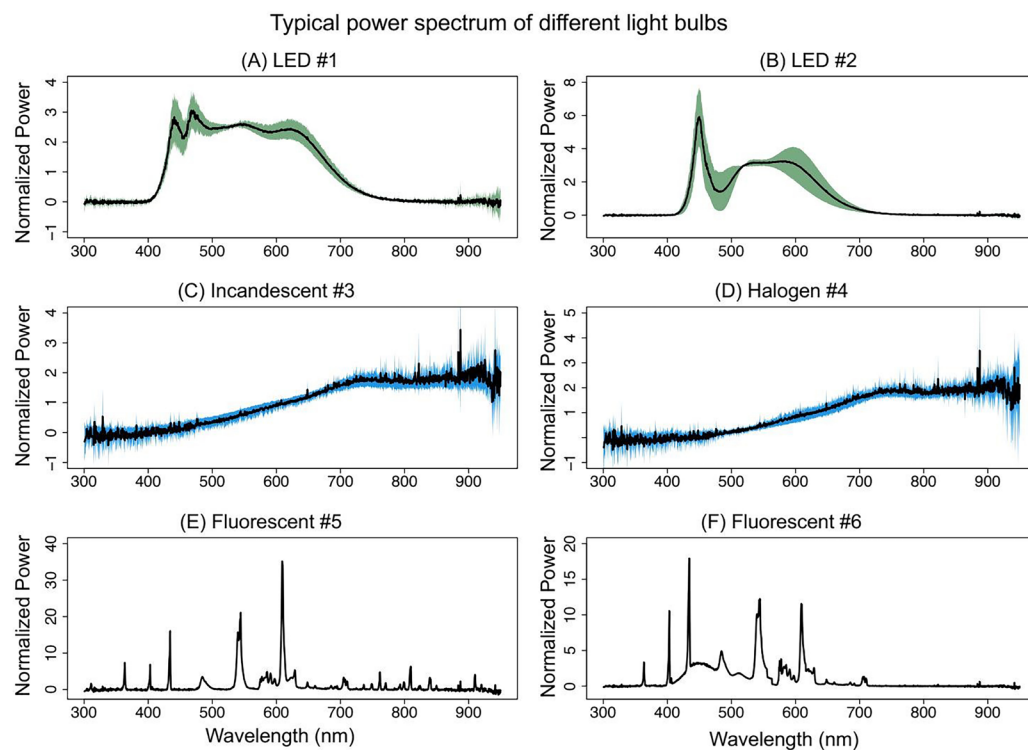


Figure 1. Comparison of standardized spectral characteristics of different bulbs in this experiment. Spectral power is normalized by the mean power across the full wavelength range to remove the influence of measurement geometry (e.g., distance and viewing angle) and enable direct comparison of spectral shapes. The analysis includes four major lighting types—light-emitting diode (LED), incandescent, halogen, and fluorescent—based on six commercial products spanning 8–60 W, representative of common household and commercial use. The samples comprise two LED bulbs: (A) Xiaoyue 8 W and (B) NVC Lighting 9 W; one incandescent bulb (C, Shisheng Lighting 60 W); one halogen bulb (D, Hexuan Lighting 42 W); and two fluorescent lamps: (E) FSL 8 W and (F) Philips 12 W (see Table 1 for details). Spectral data for each bulb were collected 5–10 times. For lamps #1–#4, the black line represents the mean standardized power, with the shaded background showing the minimum–maximum range across repeated measurements. For lamps #5–#6, due to their distinct discrete emission peaks, only the averaged standardized power is displayed.

confined to 380–680 nm, with negligible emission outside this range. Its spectrum features a pronounced peak near 450 nm and a broader band spanning 500–650 nm, with relatively smooth variations in intensity. This distribution suggests near-complete utilization of electrical energy within the visible spectrum, reflecting high lighting efficiency. However, the prominent 450 nm peak results in a slightly higher fraction of blue-light energy ($\approx 15\%$), implying a comparatively stronger blue-light component.

Illumination Characteristics of Incandescent and Halogen Lamps

Bulb #3 is an incandescent lamp that operates via the Joule heating effect, in which an electric current heats a tungsten filament to an incandescent state at approximately 2000–3000°C. At these temperatures, electrical energy is primarily converted into thermal radiation, producing a continuous spectrum spanning the visible and infrared regions (16). According to Wien's displacement law, the peak emission at such temperatures falls in the near-infrared range (≈ 0.97 – 1.45 μm), consistent with measurements showing a peak near 1000 nm. Spectral analysis further indicates that less than 15% of the emitted energy lies within the visible band (380–780 nm), rendering incandescent lamps inherently inefficient for energy-saving applications. Despite this inefficiency and a relatively short lifetime ($\sim 1,000$ hours), incandescent lamps have a simple structure and stable operation. Moreover, their negligible ultraviolet and high-energy blue-light emissions ($< 0.5\%$) confer advantages in niche applications requiring accurate color rendering or localized heating.

Halogen lamps (Bulb #4) are an improved type of electric light source based on incandescent technology. Their working principle similarly involves heating a tungsten filament to a high-temperature incandescent state via an electric current, but the bulb is filled with a halogen gas (e.g., iodine or bromine) to establish a "halogen cycle" (16). In this process, evaporated tungsten reacts with the halogen at high temperatures and is subsequently redeposited onto the filament, reducing material loss and enabling higher operating temperatures. As a result, halogen lamps achieve greater brightness and extended lifetimes compared with conventional incandescent lamps. Nevertheless, their spectral characteristics remain broadly similar, with peak emission in the infrared and a visible-light energy fraction below 15%. Ultraviolet and high-energy blue-light contributions also remain extremely low ($< 0.5\%$),

while the lamps retain the advantages of structural simplicity and operational convenience.

Illumination Characteristics of Fluorescent Lamps

Bulbs #5 and #6 are both fluorescent lamps. Such lamps typically consist of a glass tube, low-pressure gases (e.g., argon and mercury vapor), and a phosphor coating on the inner wall of the tube. The tube is filled with a low-pressure inert gas (usually argon) and a trace amount of mercury vapor. When an alternating voltage is applied, electrons emitted from the electrodes collide with gas molecules to produce a plasma, which releases characteristic ultraviolet radiation. This ultraviolet light excites the phosphor, causing it to emit visible light (17). The composition of the phosphor determines the color and spectral distribution of the lamp. Different phosphor formulations can produce light of various colors, such as cool white, warm white, or other hues, making them widely used in settings like shopping malls and supermarkets that require specific lighting.

The spectrum of Bulb #5 exhibits several distinct, sharp emission peaks concentrated mainly within the 400–650 nm range, with prominent lines at approximately 405 nm, 435 nm, 545 nm, and 585 nm. These peaks arise from mercury discharge and subsequent phosphor emission, reflecting the characteristic line spectra of mercury atoms combined with phosphor-modulated output. The emission is largely confined to the blue, green, and yellow regions, while radiation beyond 700 nm is weak, indicating minimal infrared output. Notably, three peaks at 365 nm, 405 nm, and 435 nm are non-negligible; in particular, the presence of the 365 nm ultraviolet band may pose potential health risks, especially to the eyes.

Similarly, Bulb #6 displays multiple sharp peaks within the 400–650 nm range, including those at 405 nm, 435 nm, 545 nm, and 585 nm, but with additional finer spectral features that produce a more complex structure. This complexity likely reflects differences in phosphor composition or the presence of impurities. While the spectrum continues to span the blue, green, and yellow regions, the richer peak distribution may contribute to improved color rendering. A small number of weak emissions also extend beyond 700 nm. Overall, fluorescent lamps are characterized by multi-peak spectra and high visible-light efficiency ($> 90\%$). Their ultraviolet fraction remains low ($< 2\%$, slightly higher than that of LEDs), while the proportion of high-energy blue light typically ranges from 5% to 20%, depending on lamp materials and design.

DISCUSSION

Future work should focus on reducing experimental costs and developing portable spectrometers capable of rapidly measuring the spectral distribution of various light bulbs. Currently, high-resolution commercial spectrometers cost around \$10,000, which limits their accessibility for many applications, including educational experiments and resource-constrained research. Fortunately, as the cost of core optical components continues to decline, do-it-yourself (DIY) spectrometer designs can now achieve comparable performance at more than 90% lower cost (18). The continued development of portable and affordable spectrometers could facilitate rapid spectral characterization of lighting systems and support broader applications in education, public health, and lighting research.

Several limitations of this study should also be acknowledged. First, only a subset of major lighting technologies was evaluated. Other widely used systems, particularly gas-discharge lamps such as high-pressure mercury vapor, high-pressure sodium (HPS), and metal halide lamps, remain important in industrial and outdoor applications and warrant further investigation (19). In addition, emerging solid-state lighting (SSL) technologies (19), including organic light-emitting diodes (OLEDs) and laser-based lighting systems, are advancing rapidly and should be systematically assessed for both energy efficiency and potential health impacts. Second, this study did not evaluate color temperature, which is an important characteristic influencing whether light appears warm or cool. Color temperature, expressed in Kelvin (K), is another important lighting characteristic that determines whether light appears warm or cool and can strongly influence human perception, behavior, and visual comfort (20). Integrating spectral characteristics with color temperature will therefore be essential for a more comprehensive assessment of lighting technologies.

Among lighting technologies, LEDs offer the highest energy efficiency but still pose potential risks to human eyes due to their high-energy blue-light emissions. As the most widely adopted lighting technology globally, LED-associated blue-light exposure remains a concern (21), particularly for retinal photochemical damage. To mitigate these risks while preserving energy efficiency, several strategies can be employed, including phosphor-coating adjustments, spectral engineering, and blue-light-filtering lenses (21–23). By integrating these approaches into LED design and deployment, it is

possible to reduce blue-light hazards and better protect visual health while maintaining the sustainability benefits of LED lighting.

More broadly, LEDs are part of the rapidly expanding SSL family, which also includes OLEDs and laser-based systems. SSL technologies are expected to play a central role in reducing energy consumption and greenhouse gas emissions from lighting. As noted by Zissis *et al.* (19), SSLs currently account for approximately 40–55% of the lighting market and are rapidly displacing legacy technologies. This transition could reduce global electricity use for lighting by up to ~4% by 2030 (19). Future development should focus on improving device reliability, adopting environmentally sustainable materials, and further enhancing luminous efficiency. In parallel, smart lighting systems offer additional opportunities for energy savings by dynamically optimizing light intensity, spectrum, and timing according to user demand and environmental conditions. Together, these developments could support lighting systems that simultaneously maximize energy efficiency, environmental sustainability, and human well-being.

CONCLUSION

Analysis of the experimental data reveals pronounced differences in both energy efficiency and potential health risks among the four representative light bulbs. LED lamps exhibit the highest energy efficiency, with more than 99% of emitted energy confined to the visible spectrum. However, their high-energy blue-light component (415–455 nm) can reach ~12%—within safety standards but relatively elevated—potentially increasing the risk of retinal photochemical damage under prolonged exposure. Fluorescent lamps rank second in efficiency (~92–99%) but emit 1–2% ultraviolet radiation (<380 nm) and 5–20% high-energy blue light, which may pose greater risks to eye health, including possible corneal and retinal effects, compared with LEDs. In contrast, incandescent and halogen lamps exhibit the lowest efficiency (visible-light fraction <15%), with most energy emitted in the infrared; consequently, their associated photobiological risks are comparatively low. Overall, these results highlight a fundamental trade-off between energy efficiency and light quality, providing a spectroscopic basis for evaluating the performance and health implications of different lighting technologies.

ACKNOWLEDGEMENTS

This work is mentored by Dr. Yihan Zhao from Chengdu University of Information Technology School of Optoelectronic Engineering in China.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest related to this work.

REFERENCES

- Zheng X, Streimikiene D, Balezentis T, *et al.* A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. *Journal of Cleaner Production.* 2019; 234: 1113-33. <https://doi.org/10.1016/j.jclepro.2019.06.140>
- Qu M, Shen L, Zeng Z, *et al.* Prolonged wind droughts in a warming climate threaten global wind power security. *Nat Clim Chang.* 2025; 15 (8): 842-9. <https://doi.org/10.1038/s41558-025-02387-x>
- Nair G, Gustavsson L, Mahapatra K. Factors influencing energy efficiency investments in existing Swedish residential buildings. *Energy Policy.* 2010; 38 (6): 2956-63. <https://doi.org/10.1016/j.enpol.2010.01.033>
- Mills E, Jacobson A. From carbon to light: a new framework for estimating greenhouse gas emissions reductions from replacing fuel-based lighting with LED systems. *Energy Efficiency.* 2011; 4 (4): 523-46. <https://doi.org/10.1007/s12053-011-9121-y>
- Chang Y, Wei Y, Zhang J *et al.* Mitigating the greenhouse gas emissions from urban roadway lighting in China via energy-efficient luminaire adoption and renewable energy utilization. *Resources, Conservation and Recycling.* 2021; 164: 105197. <https://doi.org/10.1016/j.resconrec.2020.105197>
- Pattison PM, Tsao JY, Brainard GC, *et al.* LEDs for photons, physiology and food. *Nature.* 2018; 563 (7732): 493-500. <https://doi.org/10.1038/s41586-018-0706-x>
- Rubinger RM, Da Silva ER, Pinto DZ, *et al.* Comparative and quantitative analysis of white light-emitting diodes and other lamps used for home illumination. *Opt Eng.* 2015; 54 (1): 014104. <https://doi.org/10.1117/1.OE.54.1.014104>
- D'Orazio J, Jarrett S, Amaro-Ortiz A, *et al.* UV Radiation and the Skin. *IJMS.* 2013; 14 (6): 12222-48. <https://doi.org/10.3390/ijms140612222>
- Gordic D, Vukasinovic V, Kovacevic Z, *et al.* Assessing the Techno-Economic Effects of Replacing Energy-Inefficient Street Lighting with LED Corn Bulbs. *Energies.* 2021; 14 (13): 3755. <https://doi.org/10.3390/en14133755>
- Ouyang X, Yang J, Hong Z, *et al.* Mechanisms of blue light-induced eye hazard and protective measures: a review. *Biomedicine & Pharmacotherapy.* 2020; 130: 110577. <https://doi.org/10.1016/j.biopha.2020.110577>
- Yen A, Shah Z, Ochoa B, *et al.* EffiSenseSee: towards classifying light bulb types and energy efficiency with camera-based sensing. *Proceedings of the 9th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation.* 9 Nov. 2022: 69-78. <https://doi.org/10.1145/3563357.3564062>
- Alebrahim MA, Bakkar MM, Al Darayseh A, *et al.* Awareness and Knowledge of the Effect of Ultraviolet (UV) Radiation on the Eyes and the Relevant Protective Practices: A Cross-Sectional Study from Jordan. *Healthcare.* 2022; 10 (12): 2414. <https://doi.org/10.3390/healthcare10122414>
- Tang X, Yang T, Yu D, *et al.* Current insights and future perspectives of ultraviolet radiation (UV) exposure: Friends and foes to the skin and beyond the skin. *Environment International.* 2024; 185: 108535. <https://doi.org/10.1016/j.envint.2024.108535>
- Li X. Differences of the Luminous Principle between Laser devices and LED devices. *E3S Web Conf.* 2020; 213: 02028. <https://doi.org/10.1051/e3sconf/202019402028>
- Barrett EM, Jeffery G. LED lighting (350-650nm) undermines human visual performance unless supplemented by wider spectra (400-1500nm+) like daylight. *Sci Rep.* 2026; 16 (1): 3061. <https://doi.org/10.1038/s41598-026-35389-6>
- Peamsuwan R, Waramit P, Worapun I, *et al.* Investigation of tungsten halogen lamp for possible usage as heat source for testing solar collector. *Energy and Built Environment.* 2024; 5 (4): 517-28. <https://doi.org/10.1016/j.enbenv.2023.04.002>
- Viana LN, Soares APS, Guimarães DL, *et al.* Fluorescent lamps: A review on environmental concerns and current recycling perspectives highlighting Hg and rare earth elements. *Journal of Environmental Chemical Engineering.* 2022; 10 (6): 108915. <https://doi.org/10.1016/j.jece.2022.108915>
- Patil VB, Khodade PS. Development and applications of an affordable DIY optical spectrometer using a webcam. *J Opt published online.* 5 June 2025. <https://doi.org/10.1007/s12596-025-02714-7>
- Zissis G, Bertoldi P. A Review of Advances in Lighting Systems' Technology-The Way Toward Lighting 4.0 Era. *IEEE Open J Ind Applicat.* 2023; 4: 111-20. <https://doi.org/10.1109/OJIA.2023.3263182>
- Mostafavi A, Xu TB, Kalantari S. Effects of

- illuminance and correlated color temperature on emotional responses and lighting adjustment behaviors. *Journal of Building Engineering*. 2024; 86: 108833. <https://doi.org/10.1016/j.jobe.2024.108833>
21. Chai Y, Yin X, Guo Z, *et al.* A novel strategy for suppressing blue light hazards of white light-emitting diodes by using transparent bamboo. *Journal of Luminescence*. 2025; 277: 120942. <https://doi.org/10.1016/j.jlumin.2024.120942>
 22. Nguyen QK, Glorieux B, Sebe G *et al.* Passive anti-leakage of blue light for phosphor-converted white LEDs with crystal nanocellulose materials. *Sci Rep*. 2023; 13 (1): 13039. <https://doi.org/10.1038/s41598-023-39929-2>
 23. Gayral B. LEDs for lighting: Basic physics and prospects for energy savings. *Comptes Rendus Physique*. 2017; 18 (7-8): 453-61. <https://doi.org/10.1016/j.crhy.2017.09.001>