Assessment of LED Lamp Performance Stability throughout Operational Periods

E.M. El-Moghazy and F. M. El-Sharkawy*
Photometry Laboratory, National Institute of Standards (NIS), Egypt
*Corresponding author's email: fatma.elsharkawy@nis.sci.eg

Article Type: Research article
Received:14/10/2024 **Accepted: 24/01/2025**

Abstract

The warm-up period of LEDs is essential for determining accurate values for parameters such as luminous flux, color temperature, and power consumption. This period affects the reliability and accuracy of measurements, as LEDs undergo changes that affect their performance characteristics. Accurate measurements during the warm-up phase are essential to avoid suboptimal usage, increased energy consumption, reduced lamp life, and variations in lighting quality. Our study measures the stability of LEDs over time for three categories of white LEDs (9, 12, and 15 W) from different lighting companies in the Egyptian market. We present detailed experimental data on electrical parameters (such as power factor and current) and optical parameters (such as luminous flux). By studying these parameters over time, we evaluate the performance of each type of lamp under typical operating conditions and identify variations in stability. The results highlight the importance of considering set-up time and settling when selecting LEDs for specific applications. Set-up times and performance characteristics vary between lamps, greatly impacting their suitability for specific environments and uses. Careful evaluation ensures optimal performance and reliability for residential, commercial, or industrial applications. This study provides valuable insights for consumers and manufacturers, helping them select and design LED lighting solutions that meet specific needs and performance criteria. Understanding the set-up behavior of LEDs contributes to more informed decisions, which improves energy efficiency and lighting quality.

Keywords: ***LED lamps, Operation time, and Color temperature.***

1 Introduction

The warm-up time for a lamp refers to the duration required for the lamp to reach a stable state and achieve its normal operating conditions, including parameters such as luminous flux, color temperature, and power consumption [1–4]. When a lamp is first turned on, it may take some time to stabilize, during which its parameters can fluctuate or change. For instance, certain types of lamps might initially exhibit a lower luminous flux than their rated value, and the color temperature might differ from the desired level. This is because the lamp's components need time to heat up and stabilize. The warm-up time can vary depending on the lamp type and its specific design. For some lamps, such as incandescent bulbs, the warm-up time might be relatively short, whereas, for LED lamps, it can take several hours to reach a stable state. Considering the warm-up time is crucial when installing or using lamps, as it impacts their performance and efficiency [5–9].

Warm-up time can vary based on several factors, including the lamp type, its age, and operating conditions. Accurate knowledge of when lamps will stabilize in terms of photometric and electrical results is essential for tasks like certification, calibration, and lighting design. The precise measurement of luminous flux is vital for lighting calculations, as indicated by the formula for exterior lighting design:

$$\mathbf{E} = \frac{N_O \, x\Phi_O \, x \, MF \, xUF}{A} \qquad (1)$$

Where:

- **E** is the average maintained illuminance.
- $\mathbf{N_o}$ is the initial number of lamps used in the installation.
- $\mathbf{\Phi_o}$ is the initial luminous flux value of the lamp.
- **MF** is the maintenance factor.
- **UF** is the utilization factor.
- **A** is the area (m^2) to be lit.

For accurate lighting calculations, precise measurement of luminous flux is required [12,13]. In addition, during calibration or testing of lamps and luminaires, electrical parameters (such as watts, current, and power factor) are critical for calculating efficiency (lumens per watt) and energy efficiency classes (EEI). The formula for EEI is:

$$\boldsymbol{EEI = \frac{P_{cor}}{P_{ref}}} \qquad (2)$$

Where Pcor is the rated power measured at nominal input voltage and corrected as needed. Correction factors are cumulative where appropriate [14,15]. For LEDs, Pref is the reference power derived from the useful luminous flux of the model (Φuse), calculated using:

For models with Φ_{use} < 1300 lumens: $P_{ref} = 0.88\sqrt{\Phi_{use}} + 0.049\ \Phi_{use}$

For models with $\Phi_{use} \geq$ 1300 lumens: $P_{ref} = 0.07341\ \Phi_{use}$

Φ_{use} is the flux measured at the integrating sphere. It is important to note that the warm-up time is not the same as the lamp's lifetime. While warm-up time refers to the period needed for the lamp to reach a stable operating state, the lifespan refers to the total duration the lamp can be used before needing replacement [16,17]. Additionally, warm-up time is influenced by the lamp's electrical and thermal characteristics. Electrical characteristics include factors such as voltage, current, and power, while thermal characteristics refer to the lamp's ability to dissipate heat generated during operation [18].

2 Material and Methods

The integrating sphere in the NIS Photometry Laboratory Figure1, with a diameter of 2.5 meters, is utilized for the routine calibration of lamps. Its walls are coated with a layer of barium sulfate, providing a diffuse reflectivity of approximately 0.97 in the visible spectrum. The sphere is equipped with a corrected filter for the luminosity function {V(λ)}, which reflects the sensitivity of the human eye to light [19]. Additionally, it features a corrected detector for the angle of incidence, a screen, and a 100 W auxiliary lamp mounted on the wall to assess self-absorption effects. A temperature sensor monitors the air temperature inside the sphere, which remains around 25 °C during lamp operation, and a spectroradiometer measures the spectral throughput of the sphere by evaluating the relative spectral irradiance of a tungsten lamp both inside and outside the sphere.

The total luminous flux of the lamps is measured directly, as it is proportional to the indirect illumination on the sphere's wall. The detector has a linear response ranging from 16-28 nA/lx, enabling the measurement of luminous flux from 0.01 lm to 106 lm through direct substitution with standard lamps. An AC power supply is connected to measure electrical parameters such as power factor, current, and wattage, with the lamps operating at a nominal voltage of (220 ± 2) V using an Aglint 6813B power supply. The lux meter also measures the Correlated Color Temperature (CCT) and Color Rendering Index (CRI) of these lamps.

Figure1: The integrating sphere system.

Figure 2: Shows the spectroradiometer to measure Color Temperature (CCT) and Color Rendering Index (CRI) for these lamps.

3 Results and Discussion

The change in luminous flux over time for various lamps demonstrates how their light output evolves as they warm up and reach a stable state. Understanding this relationship is essential for assessing lamp performance across different applications. This correlation between luminous flux and time is crucial, as it impacts the efficiency and reliability of lighting solutions, influencing both performance quality and the selection of suitable lamps for particular needs. It emphasizes the significance of warm-up and stabilization phases in determining which lamps are best suited for specific lighting requirements. Consequently, for applications that prioritize quick stabilization and energy efficiency, LED lamps emerge as the optimal choice.

This study relied on three companies in the Egyptian market to produce lighting lamps, each of which is indicated by the following symbols T, E, and V. Three lamps of different watt

(9W, 12W, 15W) were chosen from each company and given the symbol (T1, T4, and T7), (V1, V4, and V7) & (E1, E4, and E7).

The variation of luminous flux with operation time for different lamps (figure3) illustrates how the light output changes as the lamps warm up and stabilize. This relationship is critical for understanding the performance of lamps in various applications.

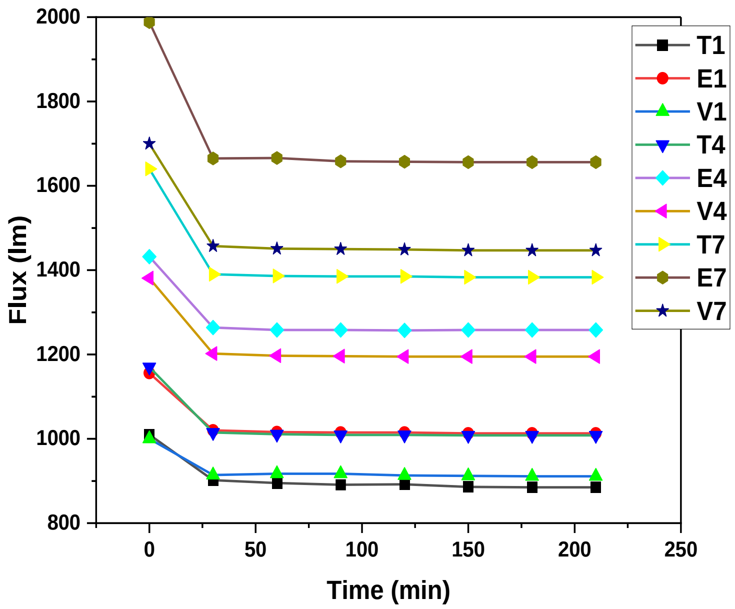

Figure 3: The luminous flux variation with operation time for different lamps.

In the above figure the initial Luminous Flux of T7, V7, E7 (15 Watts) start with the highest initial luminous flux values among their respective categories (T, V, E). The 15W lamps experience a steep drop initially, but they stabilize afterward. This indicates that the highest - wattage lamps may initially provide more luminous flux but degrade faster in terms of brightness. T4, V4, E4 (12 Watts); These mid-range wattage lamps have a slightly lower initial luminous flux compared to the 15W groups but maintain more stable performance over time. Their initial drop is less pronounced, indicating that 12W lamps might balance between initial brightness and longer-term stability. T1, V1, E1 (9Watts); The lower wattage lamps (9W) show the lowest initial luminous flux values but exhibit the most stable performance over time. The minimal change in brightness over time suggests that these lamps are designed for long-term, stable operation, even though they start with a lower brightness.

When we consider the effect of wattage, higher Wattage (15W) while initially brighter, tend to experience a more significant reduction in luminous flux as operating time progresses. This might be due to quicker wear of the components or higher strain on the lamps due to the higher power capacity. Mid-range Wattage (12W), these lamps strike a balance between initial luminous flux and stability. They show a moderate reduction in brightness but maintain a steady output for a longer period. Lower Wattage (9W) lamps are built for stability, sacrificing some initial brightness for consistent performance over time. They experience the least degradation in luminous flux, making them more suitable for applications that require long-term operation with minimal maintenance.

When we look Short-term vs. Long-term Use, 15W lamps (T7, V7, E7) are suitable for short-term applications where high initial brightness is required, but the decline in brightness over time needs to be accounted for more frequent maintenance or replacement may be necessary to maintain adequate lighting levels. While 12W lamps (T4, V4, E4) offer a good balance and may be ideal for medium-term installations where a moderate level of initial brightness is needed, along with stable performance over time. 9W lamps (T1, V1, E1) are optimal for long-term applications where stability and consistency in lighting are critical, even if the initial brightness is lower compared to the 15W and 12W systems.

3.1.Calculate the Uncertainty:

We conducted an analysis to calculate the uncertainty of luminous flux concerning operating time using statistical and mathematical methods.
The luminous flux at different operating times every half an hour was measured.
The mean luminous flux ($\bar{\Phi}$) was calculated for each time period using the formula:

$$\bar{\Phi} = \frac{1}{n}\sum_{i=1}^{n} \Phi_i \tag{3}$$

where Φ_i represents individual luminous flux values, and n is the number of measurements.
The standard deviation (σ) for the luminous flux measurements was computed as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\Phi_i - \bar{\Phi})^2}{n-1}} \tag{4}$$

The relative uncertainty (U_{rel}) was calculated as:

$$U_{rel} = \frac{\sigma}{\bar{\Phi}} \times 100\,\% \tag{5}$$

This method allowed us to quantify and analyse how luminous flux uncertainty changes with operating time effectively.

Table 1: Comparison Table of Lamp Performance Based on Relative Uncertainty.

Category	Lamp	With Start Reading (%)	Without Start Reading (%)	Best Performance
9 Volts	**T1**	4.69	0.70	Excellent without start reading
	E1	4.83	0.25	Best performance without start reading
	V1	3.32	0.28	Good but slightly less than E1
12 Volts	**T4**	5.51	0.25	Good in stable conditions
	E4	4.79	0.19	**Best overall performance**
	V4	5.35	0.22	Good but less than E4
15 Volts	**T7**	6.37	0.18	**Best in this category**
	E7	6.84	0.27	Average performance
	V7	5.98	0.25	Acceptable performance

Based on the table 1, the best lamp in each voltage category is as follows:

- **9 Volts: E1** stands out as the best, particularly without the start reading.
- **12 Volts: E4** excels as the best overall lamp under all conditions.
- **15 Volts: T7** provides the best performance with the lowest relative uncertainty.

Overall, **E4 (12 Volts)** demonstrates the highest accuracy and the lowest relative uncertainty among all the lamps.

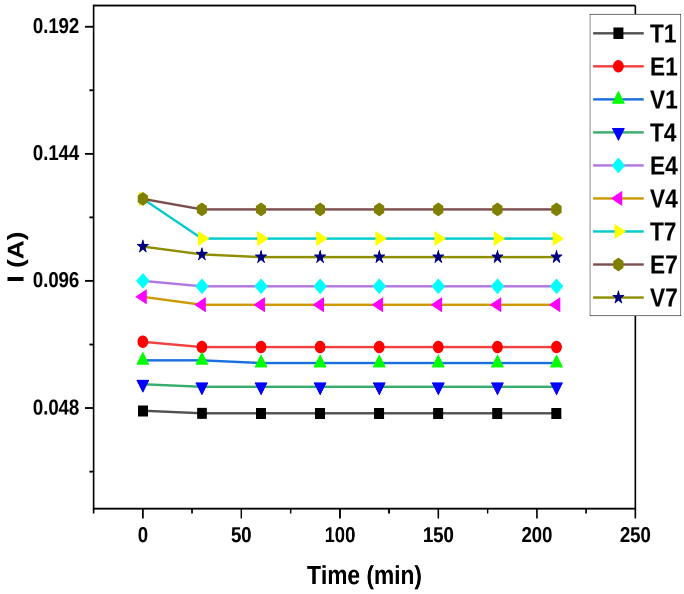

Figure 4: The current variation with operation time for different lamps.

Across all groups in figure 4, the current intensity remains relatively stable over time, which indicates that the lamps are designed to maintain a consistent current draw throughout their operational period. There are no major fluctuations or drops in the current intensity, suggesting efficient power regulation across different lamps. Similar to the figure 3 (luminous flux vs. time), there is a slight initial adjustment in some groups like T7 and E7, where the current intensity drops slightly in the early stages. However, after this initial period, the current intensity stabilizes. This could indicate that the lamps adjust to their steady-state operation quickly, with minor changes in current draw at the beginning. The stable current intensity over time suggests that these lighting systems are efficient in their power usage, without requiring significant increases in current as they operate for longer periods. This is a desirable characteristic for systems designed for long-term use. Even though the higher wattage (T7, E7, V7) have higher current intensity, they do not show any signs of increased consumption over time. This indicates good energy efficiency, especially for long-term applications where stable current draw is important.

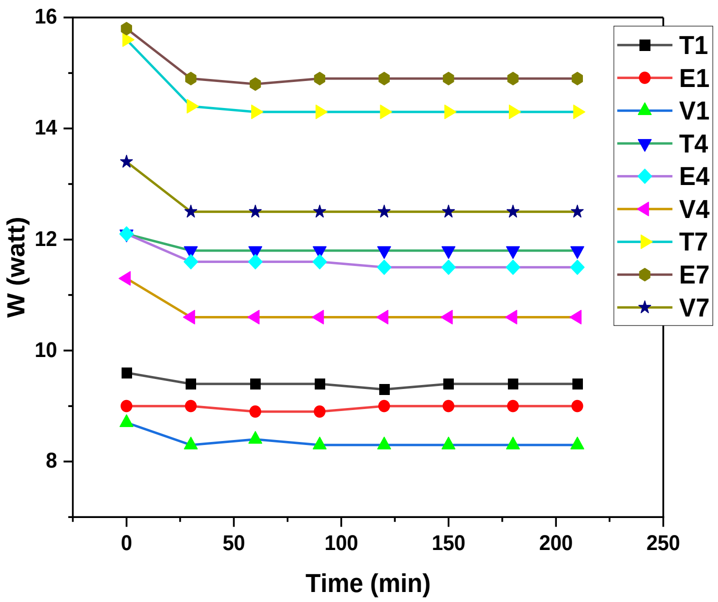

Figure 5: The power in watt variation with operation time for different lamps.

Stable Power Consumption for most groups, including T1, E1, V1, T4 and E4, the power consumption remains relatively stable over time. There are no significant fluctuations or increases in power consumption as time progresses, which indicates efficient energy management within these lighting systems. Initial Power Drop in some groups, such as E7, T7, V7and V4, there is a noticeable decrease in power consumption early in the operating time. This initial drop stabilizes shortly after, showing that the systems quickly adjust to a lower, steady power level. Despite their higher wattage, they exhibit the same trend of consistency in power consumption, confirming that higher-power systems are also energy-efficient over extended periods. When we consider the Comparison by Power Rating, 9W exhibit a lower power consumption, as expected, and remain stable after a brief initial adjustment, 12W mid-range wattage consume slightly more power but show similar stability. 15W, the higher power lamps consume the most wattage but, like the others, maintain stable consumption, indicating that even the higher wattage does not lead to increased power use over time. The stability of power consumption across all groups indicates that these lighting systems are energy-efficient and do not experience a rise in power demand over time, making them suitable for long-term applications. The initial drop in power consumption for some lamps suggests that these might be designed to adjust their power usage after an initial period of higher consumption.

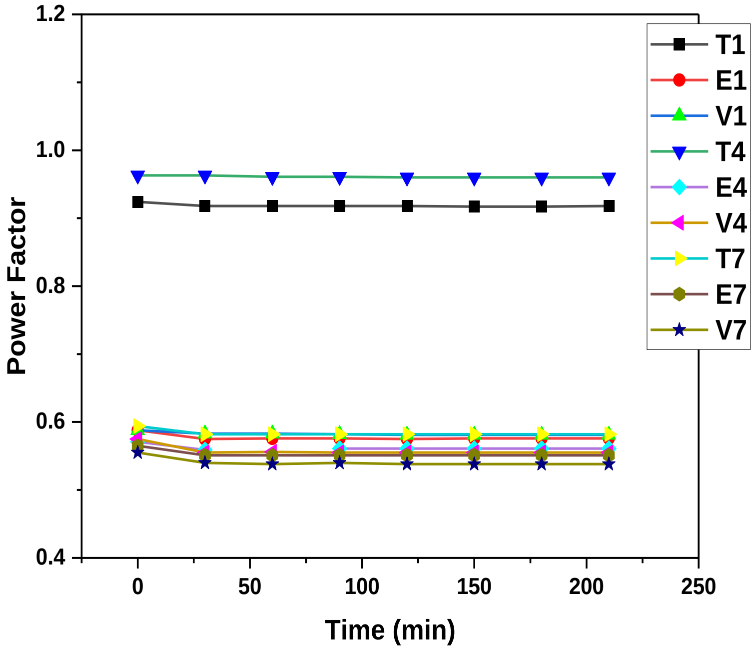

Figure 6 : The power factor variation with operation time for different lamps.

The power factor is an important parameter that indicates how efficiently the electrical power is being used by the lamps. A power factor closes to 1 is ideal, meaning most of the power is being effectively converted into light, while a lower power factor means there is more loss in the system. In the figure 6 the graph illustrates the Power Factor (PF) variation over 250 minutes of operation for three series of lamps: T-series, V-series, and E-series, each with power ratings of 9W, 12W, and 15W.

Initial Behavior (0–50 minutes): All lamps start with a fairly high-power factor close to 1.0, indicating that they are highly efficient right from the beginning. E1 (9W), E4 (12W), T7 (15W), E7 (15W), V1 (9 W), V4 (12W) and V7 (15W) all begin at nearly the same power factor level, showing efficient power usage. T1 (9W) and T4 (12W) exhibit very minimal power factor fluctuations in the early phase, maintaining a near-ideal value.

Stabilization Phase (50–150 minutes**)**: Between 50 and 150 minutes, all lamp models stabilize their power factors with almost no deviation from their initial values. The power factors remain close to 1.0 throughout this phase.

Long-Term Stability (150–250 minutes): By the end of the 250-minute period, all lamps maintain their power factors with minimal variations. T models, particularly T1 (9W), and T4 (12W), continue to perform with near-perfect efficiency, staying close to a power factor of 1.0. Higher wattage models like E7 (15W), V7 (15W) and V4 (12W) maintain slightly lower power factors but still perform efficiently in terms of power usage. There is no significant drop in power factor over time for any of the lamps.

The T1 (9W) and T4 (12W) lamps demonstrate exceptional efficiency, maintaining a near-perfect power factor of 1.0 throughout their 250-minute operation. This stability indicates highly efficient power utilization with minimal energy loss over time. Both models exhibit excellent power factor consistency, confirming their superior performance in converting electrical power into useful light without significant inefficiency.

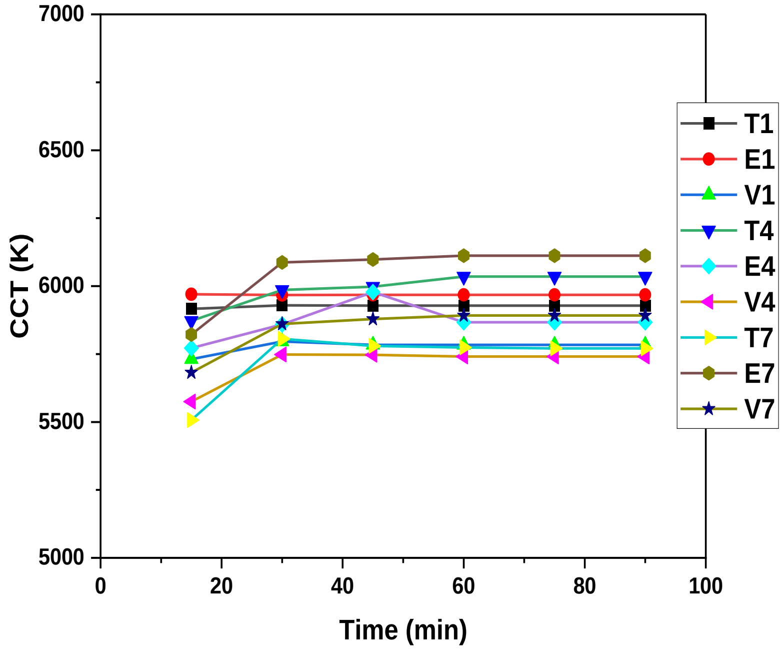

Figure 7 : The colour temperature (CCT) variation with operation time for different lamps.

The color temperature (CCT) of a lamp describes the appearance of the light it emits, measured in Kelvin (K), and can vary with operation time, this variation can be influenced by the lamp's technology, quality, and operational conditions. The graph depicts the variation in correlated color temperature (CCT) over operation time for different groups of lamps. At the beginning of the operation after 20 min there is a noticeable variation in CCT for lower watt (E1, V1 & T1) lamps. Lamps in the lower wattage range (9W) exhibit more pronounced initial changes in CCT compared to the higher wattage lamps (12W and 15W). The color temperature of all lamps tends to stabilize after the initial phase, with some fluctuations being more prominent in the higher wattage lamps. During (30-90 min) period, most lamps show a plateau or stable trend in their CCT values except V7. The T-series (T1, T4, T7) show better stability in their CCT compared E-series and V-series. Higher wattage lamps (12W and 15W) to tend to have slightly more variation than the lower wattage lamps (9W). This stabilization could be attributed to the lamp components (phosphor, electrodes) adapting to constant operational conditions.

Color Rendering Index (CRI) for Lamps is a measure used to determine how well a light source can reproduce colors accurately and naturally. Figure 8 represents the variation in Color Rendering Index (CRI) over a short operational period (100 min) for lamps categorized by power ratings.

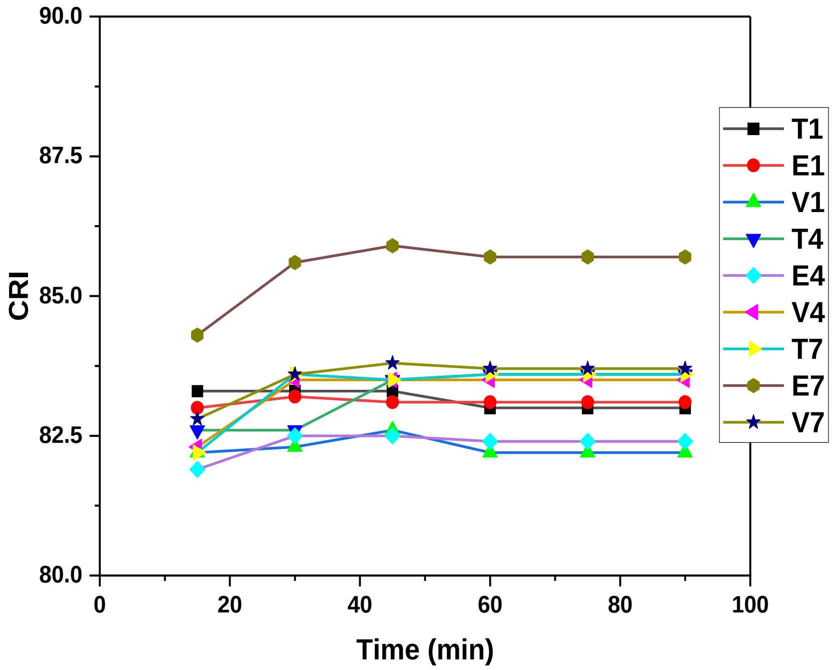

Figure 8 : The colour rendering index (CRI) variation with operation time for different lamps.

In the first few minutes, there is a rapid rise in CRI for most lamps, especially for the E7 (15W) model, which shows a sharp increase. This suggests that the CRI of the 15W lamp is adjusting quickly within this early phase. The other higher wattage lamps (T7&V7) exhibit a more gradual rise in CRI during this period, indicating a slower adjustment compared to the 9W lamps.

During the final phase of operation, from 60 to 100 minutes, all lamps achieve near-steady CRI values. The differences in CRI between the various models become negligible, indicating that the lamps have reached their optimal performance. Lower wattage lamps, such as T1 and E1, show exceptional CRI stability during this period, with minimal variation, making them more suitable for extended continuous use. In the first 30 minutes, all lamps exhibit some degree of CRI fluctuation. However, after 60 minutes of operation, the CRI levels stabilize across all models, showing very little variation as they continue running.

In the graph, the E7 lamp, possibly represented by the line approaching 90 CRI, demonstrates the best performance in maintaining high CRI values over time. This suggests that the E7 lamp might be a high-quality model or one specifically designed for optimal color rendering. While most lamps exhibit a plateau in CRI values between 30 to 60 minutes, some continue to show slight fluctuations. These variations could be attributed to factors such as the lamp's design, the materials used in its construction, and operational conditions like temperature and humidity.

4 Conclusion

The stability of LEDs is a key factor in determining their performance and reliability. How do these factors affect their performance? In terms of operating life, LEDs are designed to be long-lasting compared to traditional light sources such as incandescent or fluorescent lamps. Under ideal conditions—such as the correct voltage, proper thermal management, and appropriate ambient temperatures—LEDs can maintain their performance for many years. Performance degradation Over time, LEDs typically experience minimal performance degradation. This is because LEDs are less susceptible to wear and tear than other types of lamps. However, performance degradation can occur if LEDs are exposed to conditions outside their specified parameters, such as excessive heat or voltage fluctuations. High-quality LEDs maintain their light output and color stability much better than older technologies. This means that they not only last longer, but they also continue to provide consistent, consistent light quality throughout their life. Light output typically declines gradually, and color remains constant. The color rendering index (CRI) measures how accurately a light source displays colors compared to natural light. The color temperature (CCT) describes the appearance of the color of the light emitted, such as warm or cool white. Both the CRI and CRT can be fairly stable over the life of an LED, but this can vary depending on the specific type and quality of the LED. Higher quality LEDs tend to be more stable in CRI and CRT, which is important for applications where color accuracy is critical, such as photography or retail settings. Different types of LEDs can have different stability characteristics. For example, some types may have better CRI or CRT stability due to higher quality components or better thermal management designs. It is important to consider the specific application requirements and choose a lamp type that meets those needs. LEDs generally have good stability over time, and their long-term performance in terms of brightness output and color stability makes them a reliable lighting option. When choosing LEDs, it is helpful to consider the type and quality to ensure that your specific CRI and CRT stability needs are met.

The observed difference in the relative uncertainty (($\mathbf{U_{rel}}$) with or without the starting reading highlights the impact of performance stability during the initial moments of bulb operation compared to its subsequent steady state. Selecting the best bulb involves prioritizing those with lower uncertainty, as this reflects greater performance stability and improved measurement accuracy.

5 Declarations

5.1 Study Limitations

None.

5.2 Funding source

None.

5.4 Competing Interests

The authors have no financial or proprietary interests in any material discussed in this article.

5.5 Ethical Approval

Not Required

References

[1] Iqbal M.N., Jarkovoi M., Kütt L., and Shabbir N. Impact of LED Thermal Stability to Household Lighting Harmonic Load Current Modeling, 2019 Electr. Power Qual. Supply Reliab. Conf., 2019 Symp. Electr. Eng. Mechatronics, Vol. -, Issue -, P. 1–6 (2019). https://doi.org/10.1109/PQ.2019.8818226.

[2] Fay C.D. and Nattestad A. Optical Measurements Using LED Discharge Photometry (PEDD Approach): Critical Timing Effects Identified & Corrected, IEEE Trans. Instrum. Meas., Vol. 71, Issue 7, P. 1–9 (2022). https://doi.org/10.1109/TIM.2021.3137155.

[3] Skarżyński K., Żagan W., and Krajewski K. LED Luminaires: Many Chips—Many Photometric and Lighting Simulation Issues to Solve, Energies, Vol. 14, Issue -, P. - (2021). https://doi.org/10.3390/en14154646.

[4] Ma L., Liu Y., Liu J., Guo S., Pei X., Sun F., and Fang S. A fast LED calibration method under near field lighting based on photometric stereo, Opt. Lasers Eng., Vol. 147, Issue - , P. 106749 (2021). https://doi.org/10.1016/j.optlaseng.2021.106749.

[5] Ikonen E. Recent advances and perspectives in photometry in the era of LED lighting, Meas. Sci. Technol., Vol. 35, Issue -, P. 21001 (2024). https://doi.org/10.1088/1361-6501/ad0de6.

[6] Czyżewski D. The Photometric Test Distance in Luminance Measurement of Light-Emitting Diodes in Road Lighting, Energies, Vol. 16, Issue -, P. - (2023). https://doi.org/10.3390/en16031199.

[7] Krüger U., Ferrero A., Mantela V., Thorseth A., Trampert K., Pellegrino O., and Sperling A. Evaluation of different general V(λ) mismatch indices of photometers for LED-based light sources in general lighting applications, Metrologia, Vol. 59, Issue -, P. 65003 (2022). https://doi.org/10.1088/1681-7575/ac8f4d.

[8] Cai M., Yang D., Mo Y., Huang J., Yin L., Yang L., Chen X., Chen W., and Zhang G. Determining the thermal stress limit of LED lamps using highly accelerated decay testing, Appl. Therm. Eng., Vol. 102, Issue -, P. 1451–1461 (2016). https://doi.org/10.1016/j.applthermaleng.2016.04.012.

[9] Yang Z., de Boer T., Braun P.M., Su B., Zhang Q., Moewes A., and Xia Z. Thermally Stable Red-Emitting Oxide Ceramics for Laser Lighting, Adv. Mater., Vol. 35, Issue -, P. 2301837 (2023). https://doi.org/10.1002/adma.202301837.

[10] Valetti L., Piccablotto G., Taraglio R., and Pellegrino A. Long-Term Monitoring Campaign of LED Street Lighting Systems: Focus on Photometric Performances, Maintenance and Energy Savings, Sustainability, Vol. 15, Issue 24, P. 152416910 (2023). https://doi.org/10.3390/su152416910.

[11] Doğanşahin K., Ayaz R., Bozkurt A., and Kekezoğlu B. Assessment of photometric and electrical measurements of residential light sources, Electr. Eng., Vol. 103, Issue -, P. 2075–2086 (2021). https://doi.org/10.1007/s00202-021-01217-5.

[12] Jamaludin M.H., Wan Ismail W.Z., Husini E.M., and Bahror N.A.M. Investigation of photometric distribution of LED and HSPV for road lighting, J. Eng. Appl. Sci., Vol. 70, Issue -, P. 112 (2023). https://doi.org/10.1186/s44147-023-00286-6.

[13] Rahman M.T., Haque M., and Akhtaruzzaman M. Photometric Analysis in Designing 5G Enabled Smart Indoor-Campus Network Using VLC, in: 2024 6th Int. Conf. Electr. Eng. Inf. Commun. Technol., P. 992–996 (2024). https://doi.org/10.1109/ICEEICT62016.2024.10534339.

[14] Akashi Y., Ohashi R., and Uchida T. The Effect of Luminance Reduction on Foveal Task Performance while Implementing Mesopic Photometry in Street Lighting Standards, J. Sci. Technol. Light., Vol. 47, Issue -, P. IEIJ220000656 (2024). https://doi.org/10.2150/jstl.IEIJ220000656.

[15] Singh S., Ahuja H., and Srivastva R.K. Measurement of color, photometry and electrical parameters of street light LEDs, Mater. Today Proc., Vol. 65, Issue -, P. 3488–3495 (2022). https://doi.org/10.1016/j.matpr.2022.06.060.

[16] Moyano D.B., Moyano S.B., López M.G., and Aznal A.S. Photometric and colorimetric analysis of light emitting diode luminaires for interior lighting design, Color Res. Appl., Vol. 46, Issue -, P. 791–807 (2021). https://doi.org/10.1002/col.22616.

[17] Weiqiang Z., Jinyun Y., Hui L., Ying S., and Yandong L. Temperature dependence correction method of LED filament lamp for total luminous flux calibration based on voltage measurement, Metrologia, Vol. 58, Issue -, P. 45003 (2021). https://doi.org/10.1088/1681-7575/abfe3e.

[18] Zhao W., Yan J., Liu H., Su Y., and Lin Y. Characterization of the LED filament lamp for luminous intensity calibration, Metrologia, Vol. 60, Issue -, P. 25004 (2023). https://doi.org/10.1088/1681-7575/acb70e.

[19] Wang R., Yu J., Zhang X., Tang Q., and Liu X. A calibration method for LED point light sources in near-field photometric stereo, in: H. Wang, Q. Kemao, C.H. Dang, A.J. Danner, F. Cheng (Eds.), Int. Conf. Opt. Photonic Eng. (IcOPEN 2023), SPIE, P. 45 (2024). https://doi.org/10.1117/12.3023291.