Assessing Light Pollution from Streetlight Designs along Major Streets in Kota Kinabalu Towards Sustainable Urban Lighting

Farah Asyikin Abd Rahman[1]*, Ummi Kalsom Noor Din[1], Charlos Chin Yin Yong[1], and Murniati Imam Supaat[2]

[1]Department of Electrical Engineering,
Politeknik Kota Kinabalu,
No. 4, Jalan Politeknik, KKIP Barat, KKIP, 88460, Kota Kinabalu, Sabah, Malaysia.

[2]Significant Technologies Sdn Bhd,
No. 12, Jalan Dagang SB 4/1, Seri Kembangan, Selangor, Malaysia.

*Corresponding Author's Email: farahasyikin@polikk.edu.my

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Abstract
Light pollution from streetlights is becoming an increasingly serious issue, impacting ecosystems, human health, and astronomical visibility. In Kota Kinabalu, efforts to address the effects of street lighting remain limited, resulting in low public awareness of its consequences. This study examined light pollution in two major streets in Kota Kinabalu: Jalan Tun Fuad Stephens and Jalan Pasir by measuring the brightness and visible spectrum of streetlights using a digital lux meter and smartphone camera equipped with 500 lines/mm diffraction gratings. The collected data were analysed to assess how streetlight designs affect the environment, with a focus on comparing theoretical and measured lux and lumen values. The findings revealed that the installed streetlight bulbs contributed to light pollution, particularly through lux levels that exceeded standard limits by 60%, as well as the emission of potentially harmful wavelengths such as blue and violet light. These results offer valuable insights that can help shape better urban lighting designs. Additionally, the findings can assist local governments in balancing public safety, energy efficiency, and environmental protection in street lighting designs. Future studies should expand to other areas, such as Tawau and Semporna, where sea turtle populations are common. This would help protect these creatures from the adverse effects of artificial lighting on marine ecosystems. Finally, wavelength measurements in future research could be refined using a spectral light meter to enhance accuracy.

Keywords: Environmental Impact, Light Pollution, Spectral Analysis, Street Lighting, Urban Sustainability

1.0 Introduction
The rapid growth of urban populations, driven by rural-to-urban migration and the pursuit of a higher quality of life, has transformed traditional, self-sufficient cities into expansive megacities. This urban expansion has led to numerous environmental challenges, commonly categorised into four key areas: water, waste, air, and light pollution [1]. Among these, light pollution has emerged as a significant concern due to its adverse effects on ecosystems, human health, and astronomical visibility. Light pollution occurs when

artificial lighting, particularly from streetlights, excessively brightens the night environment, leading to phenomena such as light trespass and sky glow. These effects obscure the view of celestial wonders and disrupt natural ecosystems. Moreover, the widespread adoption of energy-efficient LED street lights, while beneficial for reducing energy consumption and combating climate change, has exacerbated light pollution. These problems are too complex to be addressed with traditional urban approaches, which often fail to meet the needs of today's urban dwellers. To tackle these issues effectively, a scientific and technological approach is necessary, leading to the concept of the smart city [1], [2].

For instance, in Berlin, Germany, the focus lies on reducing light pollution through the utilisation of a data resolution meter. It was identified that the primary source of light pollution in the area was from streetlights [3]. Similarly, in Hong Kong, efforts are directed towards decreasing light brightness, employing sky quality meters and sky light level measurements. The examination reveals that spotlights and various types of lighting from shops contribute significantly to street-level light pollution. Furthermore, the impact of these sources varies depending on factors such as shop profile and size [4]. Equally significant, in Shah Alam, Malaysia, the aim is to curb light pollution, particularly the brightness of the night sky, using sky quality meters for assessment. Geographical Information System (GIS) data from June 2021 reveals a concerning trend in Shah Alam, where the light pollution not only diminishes nighttime visibility but also contributes to energy wastage and environmental impacts like light trespass and sky glow [5]. In the Netherlands, Dr. Schreuder's research targets the mitigation of light trespass by narrowing the spectral range of emitted light [6]. On the other hand, according to a 2018 statement by the Consumers' Association of Penang, approximately 30% of outdoor lights locally suffer from poor design. Out of this, only 40% effectively illuminates the ground, while an additional 10% causes glare. The remaining 50% is wasted by emitting light sideways and upwards, resulting in light trespass [7].

Light pollution, like other forms of pollution, has far-reaching effects on the natural world and has become a significant environmental issue [1]. Its widespread impact disrupts ecosystems and contributes to systemic changes, underscoring the need to address its consequences alongside advancements in urban lighting. As light pollution increases, the harmful effects of blue light wavelengths emitted by streetlights have become a growing concern. Research shows that this type of pollution negatively affects insects and amphibians, which are integral to ecological balance [3]. In Sabah, near Masjid Bandaraya in Kota Kinabalu, this issue is particularly alarming due to its impact on the endangered Chinese Egret, a migratory bird that relies on the area's tidal flats and estuaries for feeding during its autumn and winter migration. Light pollution disrupts the egret's ecosystem, threatening its survival. With fewer than 10,000 individuals remaining in 2020, the species faces increasing risks from environmental changes caused by artificial lighting [8], [9].

Despite the growing recognition of light pollution's environmental effects, only a handful of local studies have been conducted to explore the impact on various environmental or observational aspects in Malaysia. These studies examine various aspects, particularly the effects of artificial light on either astronomical visibility or ecological systems [10], [11], [12], [13]. However, no research has specifically addressed the impact of artificial light on the key streets of Kota Kinabalu. This lack of focused studies has resulted in limited public awareness and understanding of the issue, highlighting the urgent need for targeted research to inform sustainable urban lighting solutions. Thus, this paper presents a study assessing streetlight pollution levels along two major streets in Kota Kinabalu, i.e. Jalan Tun Fuad Stephens and Jalan Pasir. The objective is to quantify the streetlight illuminance and spectral characteristics using a digital lux meter and a smartphone-based spectrometer.

1.1 Streetlight Pollution

Many places are switching from traditional, less energy-efficient sodium streetlights to LED streetlights. LEDs use much less energy, making them a useful tool in fighting climate change. They also cost local governments less to power and maintain [14], [15], [16]. However, this change has led to more blue spectrum light and medical experts and scientists caution that if LEDs are not used properly, they could harm people, wildlife, and the environment [14], [15]. Streetlights with LEDs typically emit white light, while sodium lamps produce a yellowish glow, as shown in Figure 1. White LEDs emit light across the entire visible spectrum, and the more colours they emit, the more likely they are to disrupt various species and natural processes [14], [15], [17], [18], [19]. In contrast to popular belief, high-pressure sodium (HPS) lamps also emit light across the visible spectrum, even though their glow appears yellowish orange [20], [21].

Figure 1: A comparison of sodium lights (on the left) and white LEDs (on the right) [18]

Brighter streets lead to brighter skies, and more lights at night harm all living things. Researchers in England found that LED streetlights reduce nocturnal moth caterpillar populations by 50%, and billions of migrating birds struggle to navigate in the ever increasingly illuminated skies [15]. Insects' mating and pollination are also affected, which has scientists concerned that light pollution is disrupting ecosystems [14], [15], [17], [18], [19]. There is growing evidence that insect populations, especially moths, have declined in recent decades, with significant losses in parts of Europe. Moths play an important role in ecosystems as pollinators, prey, and hosts for other species, so their decline could have wide-reaching impacts on biodiversity and ecosystem health [14], [15], [17], [18], [19]. Figure 2 depicts such a situation.

Nonetheless, even though high-pressure sodium (HPS) lamps emit weak blue light wavelengths, the accumulated exposure to blue light can have negative effects on human health, wildlife, and the night sky [20]. As insect populations decline and light pollution increases, it is important to address the harmful effects of blue light wavelength streetlights. Research shows that this pollution harms not only insects but also amphibians [22]. This is especially concerning in Sabah, near Masjid Bandaraya in Kota Kinabalu, a key stop for the egret bird species during its autumn and winter migration [23]. The Chinese Egret feeds on fish, crustaceans, worms, and other small animals in tidal flats and estuaries [24]. The disruption caused by light pollution threatens the egret's ecosystem, and the species, already endangered with fewer than 10,000 individuals in 2020, is at risk [25].

Figure 2: LED streetlights illuminate wildlife oases, such as grass road verges, hedgerows, and field margins [18], preventing female caterpillars from laying eggs and contributing to population declines.

1.2 Jalan Tun Fuad Stephen and Jalan Pasir

Jalan Tun Fuad Stephens and Jalan Pasir are two notable streets in Kota Kinabalu, Sabah. The streets are located approximately 4 to 5 kilometres from the city centre. One of the key landmarks on these streets is the Masjid Bandaraya Kota Kinabalu, also known as the 'Floating Mosque' due to its location by a man-made lagoon. The man-made lagoon near the Masjid Bandaraya Kota Kinabalu is an important stop for egrets and other wading birds. This lagoon provides a suitable habitat for these birds, offering them a place to rest and feed. The presence of such wildlife adds to the scenic beauty and ecological significance of the area, as shown in Figure 3.

Figure 3: A comparison of sodium lights (on the left) and white LEDs (on the right) of the Masjid Bandaraya Kota Kinabalu [26].

2.0 Methodology

The methodological procedures of this study began with aligning the work of this project with the main objective (red, blue and yellow) of the study, as illustrated in the flow chart shown in Figure 4. This flowchart shows how each objective was achieved through a clear and organised plan. It outlined the steps and methods that were followed to reach each goal, making it easy to understand how the project moved forward and ensuring all key areas were addressed.

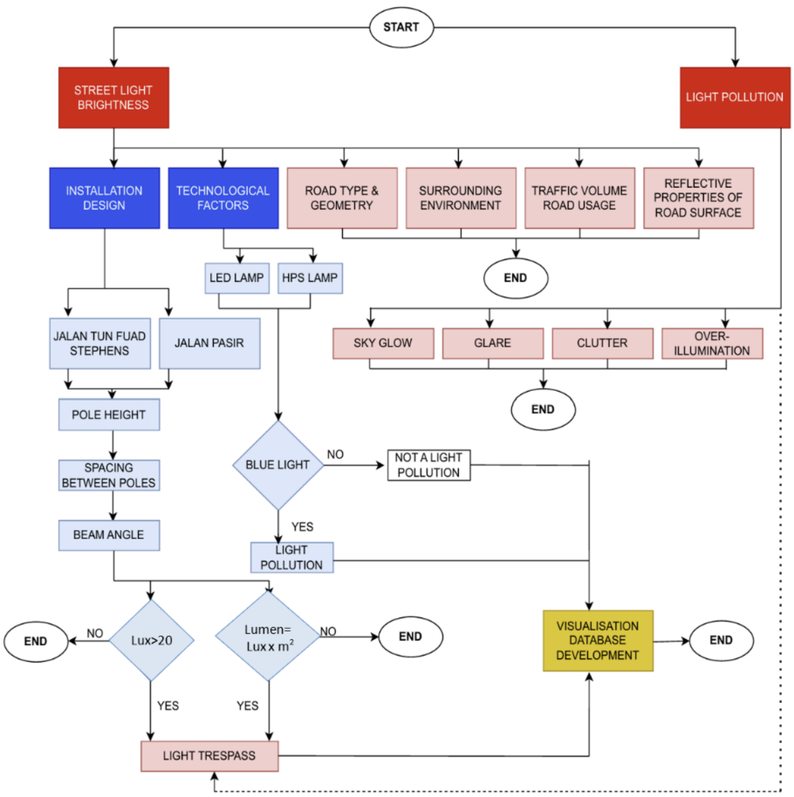


Figure 4: A flowchart that shows how each objective was achieved

Regrettably, according to the Light Pollution Atlas 2022, this site contributes significant light pollution, as shown in Figures 5 and 6.

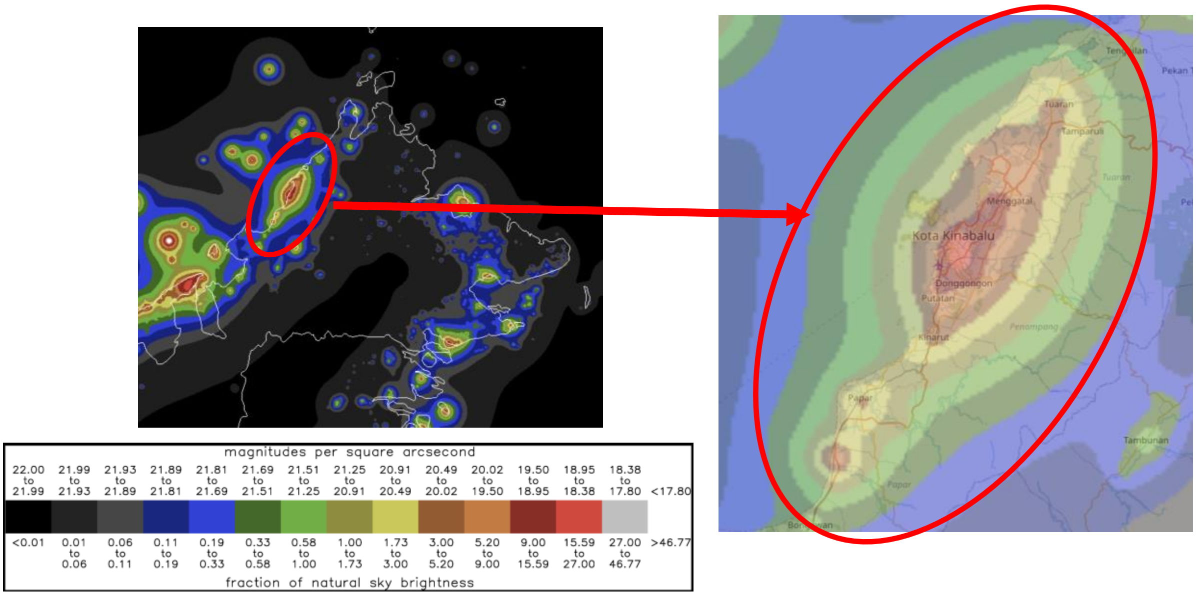
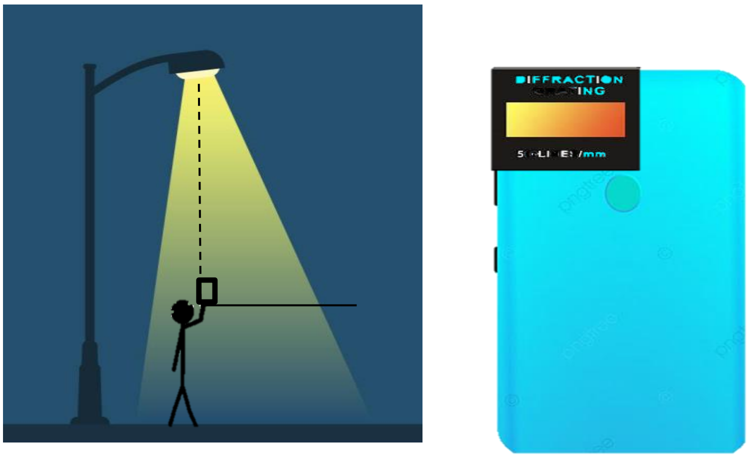


Figure 5 (left): Light pollution Atlas 2022 (Sabah) and (right): The intensity of light pollution in Kota Kinabalu, Sabah [27].

Figure 6: The second-highest recorded ratio of artificial light against natural brightness in Sabah (Jalan Tun Fuad Stephens) and the third-highest recorded ratio of artificial light against natural brightness in Sabah (Jalan Pasir) [27], [28].

Next, the procedures for streetlights' lux levels measurement and the classification of the captured spectral data from the streetlights were done. Figure 7(a) illustrates the method of recording the amount of streetlight illumination on a surface over a given area using a lux meter. The measurement must be taken at a 90-degree angle from the light source, ensuring that no obstacles such as trees or other objects interfere with the reading. Furthermore, weather conditions can affect the measured lux values. On rainy nights, the value of lux decreases due to rainwater disruption. The recorded lux values were then served as input to determine the lumen output of the streetlights, which represents their brightness. By assessing the spectrum, lux and lumen of the streetlights, the extent of light trespass can be effectively evaluated. This approach provides valuable insights into the severity of light pollution, particularly in Jalan Tun Fuad Stephens and Jalan Pasir. Figure 7(b) depicts the use of a 500 lines/mm spectral diffraction grating glass and a 40MP, f/1.8, 27mm (wide), 1/1.7", PDAF smartphone camera (P30) to capture the spectral data, facilitating the analysis of the light spectrum emitted by the streetlights. Due to the unavailability of a spectral light meter, this method employed the next best alternative, i.e. using a diffraction grating and smartphone camera setup. The spectral glass must be placed horizontally with the smartphone camera to ensure a clear light spectrum is captured for accurate analysis.



(a) (b)

Figure 7: (a) Best practices for measuring streetlight intensity in lux, (b) The placement of the spectral glass in front of the smartphone camera

In brief, the streetlight designs are as follows:

i. Jalan Tun Fuad Stephens: The section under study is 650 meters long and features 20 selected streetlights designed with HPS lamps, each 10 meters in height. The beam angle is observed to be 90 degrees [28], [29].
ii. Jalan Pasir: The section under study is 300 meters long and features 10 selected streetlights designed with HPS lamps, each 10 meters in height. The beam angle is observed to be 90 degrees [28], [29].
iii. Lumen: The measurement of the total quantity of visible light emitted by a source, e.g. light bulb [30]
iv. Lux: The measurement of the illumination intensity at a specified surface, e.g. road [30].
v. Illuminance (E) is the luminous flux incident on a surface per unit area or the photometric flux density. It is expressed in lumens per unit area [29].

3.0 Results and Discussion

Figures 8 – 11 highlight the primary objective of this study, which was to analyse how the brightness of streetlights on Jalan Tun Fuad Stephens and Jalan Pasir contributes to light pollution in the surrounding areas. It is important to note that decorative lighting elements in the vicinity did not influence the results, as the analysis was confined to street segments devoid of any decorative lights or LEDs. By comparing the measured and theoretical values of lux and lumens, the findings indicate that the installed streetlights significantly contribute to light pollution. In simpler words, higher measured lux levels reflect increased brightness, which corresponds to a higher lumen output. This rise in lumen leads to the spread of excessive light into unintended areas, contributing to light pollution. Streetlights should be designed to direct illumination solely onto roads and pedestrian areas. However, when over-illumination occurs and light spills into nearby sanctuaries, it can unintentionally disturb nocturnal wildlife. This inference is further supported by the recorded ratio of artificial light to natural light, as shown in Figure 5.

As shown in Figure 8, the chart compares theoretical and measured lux values for the 20 installed streetlights along the 650-meter Jalan Tun Fuad Stephens. The theoretical lux value, based on IEC and ISO street lighting standards [31], is set at 20 lx. However, the measured lux values range between 28 lx and 32 lx, which were significantly exceeding the theoretical reference. Meaning the lighting system is providing more illumination than the standard requirement. The highest recorded value (32 lx) surpasses the standard by 60%, suggesting potential over-illumination or an over-engineered lighting system. This excess brightness may contribute to unnecessary energy consumption and increased light pollution [32]. Moreover, over-illumination alters the natural behaviour of nocturnal wildlife and highlights the need for more focused and environmentally conscious lighting designs.

In addition, Figure 9 presents a comparison chart of theoretical and measured lumen values for the same installed streetlights on Jalan Tun Fuad Stephens. The theoretical lumen value, based on the Public Works Department (JKR) standard calculation (1 lux (lx) = 1 lumen/m^2), was determined to be 6283.2 lm [29]. However, the measured values, ranging from 8796.5 lm to 10053 lm, exceed the theoretical estimates by 40% - 60%, reinforcing the earlier indication of an over-engineered lighting system. Such overdesign can contribute to excessive energy use and more severe light pollution.

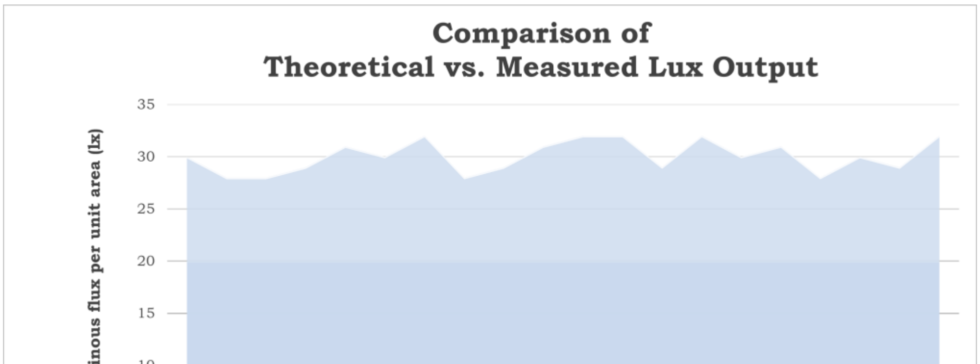
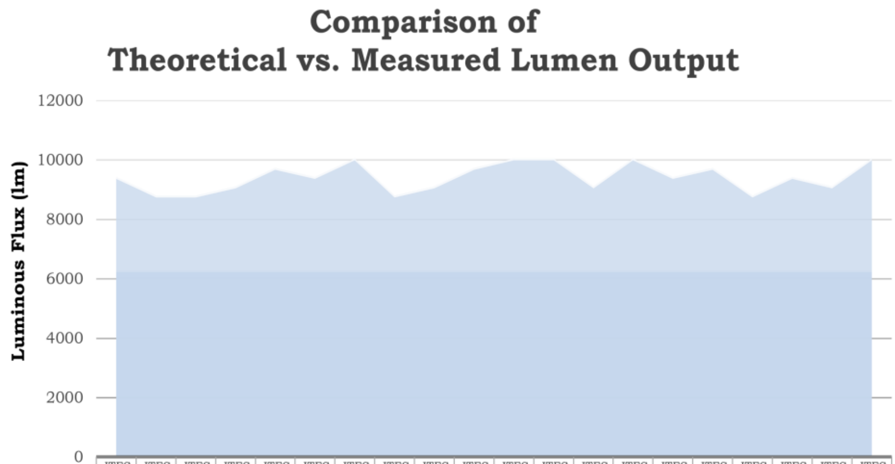


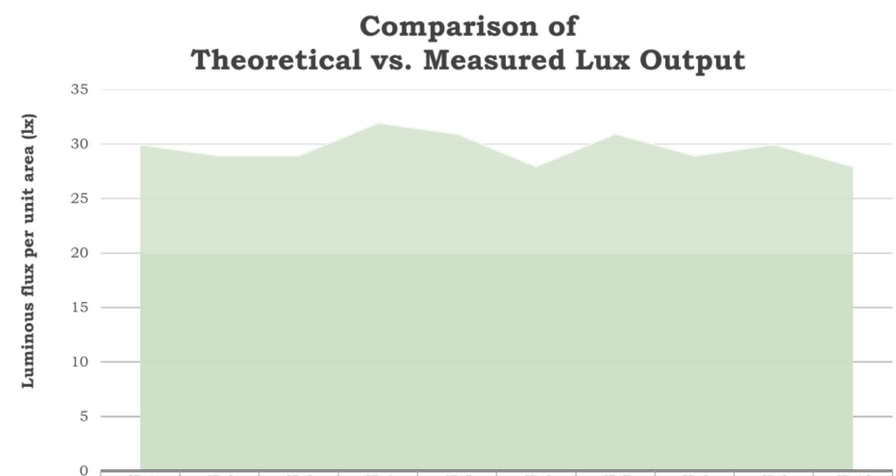
Figure 8: Comparison between theoretical and measured lux output of streetlights at Jalan Tun Fuad Stephens



	JTFS 1	JTFS 2	JTFS 3	JTFS 4	JTFS 5	JTFS 6	JTFS 7	JTFS 8	JTFS 9	JTFS 10	JTFS 11	JTFS 12	JTFS 13	JTFS 14	JTFS 15	JTFS 16	JTFS 17	JTFS 18	JTFS 19	JTFS 20
Lumen (Theoretical)	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283	6283
Lumen (Measured)	9425	8796	8796	9111	9739	9425	10053	8796	9111	9739	10053	10053	9111	10053	9425	9739	8796	9425	9111	10053

Figure 9: Comparison between theoretical and measured lumen output of streetlights at Jalan Tun Fuad Stephens

On the other hand, Figures 10 and 11 present comparison charts of the theoretical and measured lux and lumen values, respectively, for the 10 installed streetlights along the 300-meter stretch of Jalan Pasir. As previously mentioned, the theoretical lux value, based on IEC and ISO street lighting standards [31], is set at 20 lx. Interestingly, the recorded measured lux closely resembles that of Jalan Tun Fuad Stephens, as shown in Figure 10, with the highest recorded value exceeding the standard by 60%. Nonetheless, Figure 11 presents a comparison chart of theoretical and measured lumen values for the installed streetlights on Jalan Pasir. The luminance flux was calculated to be 6283.2 lm. The measured luminous flux values ranged from 8796.5 lm to 10053.1 lm, with the highest recorded at JP4 and the lowest at JP6 and JP10. Compared to the theoretical value, these measurements exceed expectations by 40% to 60%, indicating a substantial overdesign.



	JP 1	JP 2	JP 3	JP 4	JP 5	JP 6	JP 7	JP 8	JP 9	JP 10
Lux (Theoretical)	20	20	20	20	20	20	20	20	20	20
Lux (Measured)	30	29	29	32	31	28	31	29	30	28

Figure 10: Comparison between theoretical and measured lux output of streetlights at Jalan Pasir

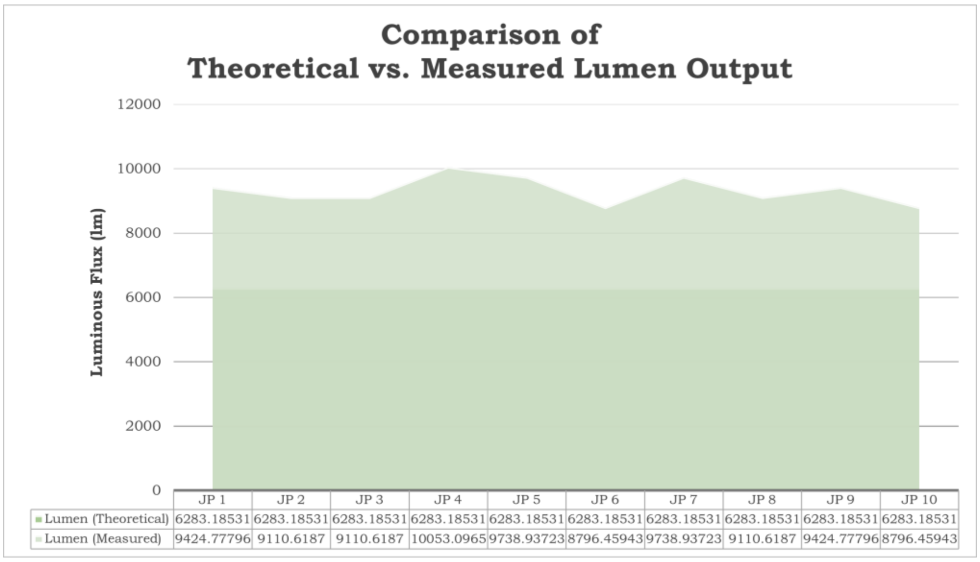


Figure 11: Comparison between theoretical and measured lumen output of streetlights at Jalan Pasir

Next, Figure 12 presents the visible spectrum emitted by the streetlights along Jalan Tun Fuad Stephen and Jalan Pasir, captured using a 500 lines/mm spectral diffraction grating and a 40MP, f/1.8, 27mm (wide), 1/1.7" PDAF smartphone camera (P30). It is important to acknowledge the limitations of using a smartphone camera, which may affect spectral wavelength accuracy. While the presence of blue-wavelength light supports the earlier assumption that high-pressure sodium (HPS) lamps emit across the visible spectrum, despite their yellowish-orange glow. Nonetheless, the greater the number of HPS lamps installed, the broader the range of emitted wavelengths, leading to increased exposure to blue light, which may have negative effects on human health, wildlife, and the night sky.

(a) (b) (c)

Figure 12: The recorded visible spectrum of streetlights (a) and (b) on Jalan Tun Fuad Stephens and (c) Jalan Pasir

4. Conclusion

In conclusion, this study aimed to assess the design and spectral composition of installed streetlights to support sustainable urban lighting solutions. The study successfully achieved its objectives by analysing data that confirmed a direct correlation between the streetlights on Jalan Pasir and Jalan Tun Fuad Stephens and increasing light pollution levels, particularly light trespass. The assessment also verified that blue light is emitted from the streetlights at both locations. The use of a smartphone camera and diffraction grating effectively captured and analysed the light spectra, providing valuable insights for improving urban lighting designs. These findings can help local governments balance public safety, energy efficiency, and environmental protection in city lighting practices. For future research, the study should be extended to other areas, such as Tawau and Semporna, where sea turtles are commonly found. Investigating light pollution in these regions could contribute to protecting wildlife from artificial lighting exposure. Additionally, streetlight wavelength measurements can be further refined using a spectral light meter to enhance accuracy. Expanding this research to include the surrounding environment is also crucial, as observations indicate that decorative LED lighting at Masjid Bandaraya may be affecting the nearby wetland ecosystem. This highlights the need for a deeper investigation into how such urban installations interact with natural habitats. Overall, the findings establish a foundation for urban lighting strategies that balance public safety, energy efficiency, and ecological sustainability.

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Author Contributions

Farah Asyikin Abd Rahman: Conceptualisation, Data Curation, Validation, Formal Analysis, Investigation, Writing – Review & Editing, Resources, Supervision, Project Administration;
Ummi Kalsom Noor Din: Methodology, Data Curation, Validation, Formal Analysis;
Charlos Yong Chin Yin: Methodology, Investigation, Writing – Original Draft;
Murniati Imam Supaat: Validation, Writing-Reviewing.

Conflicts of Interest

The authors declare no conflict of interest. The organisations had no influence on the study design; data collection, analysis, or interpretation; the writing of the manuscript, or the decision to publish the results. This manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have reviewed and approved the final version of the manuscript for publication.

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