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REPLACEMENT OF TUBULAR FLUORESCENT LAMPS WITH TUBULAR LEDS LAMPS AND DAYLIGHT INTEGRATION IN CLASSROOMS AND LABORATORIES

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ABSTRACT

The quality of lighting significantly influences our ability to perform tasks in enclosed spaces, and certain characteristics of lighting sources play a crucial role. Light-emitting diode (tubular LED) lamps offer advantages for both home and office use. Choosing tubular LED lamps over fluorescent ones is beneficial for several reasons. Tubular LEDs are mercury-free, ensuring environmental safety compared to the small amount of mercury present in fluorescent tubes. Furthermore, tubular LEDs provide directional lighting, minimizing light loss in fixtures and unnecessary areas, and offering better efficiency (around 40% more than tubular fluorescent lamps). Also, they produce high-quality light with various color temperatures, eliminating flickering issues that can cause discomfort such as eye strain, headaches, and migraines. Additionally, tubular LEDs have a longer lifespan making them a preferable lighting option. The superior quality of natural light makes it the optimal source of illumination, which matching well with the visual response of the human eyes. Daylight has a positive influence on people, instilling a feeling of vibrancy and brightness within their living environment. The acknowledged benefits of daylight extend to enhancing visual comfort, promoting health, and improving overall performance among building occupants. This paper focuses on the integration of natural daylight with artificial light, particularly through tubular LED lamps, and investigates the daylight factor. Two groups of six tubular LED lamps (60cm with 9 Watt and 120cm with 18 Watt) and another group of six tubular fluorescent lamps (60cm with 18 Watt and 120cm with 36 Watt) were studied. The study involved two sets of six tubular LED lamps (60cm with 9W and 120cm with 18W) and another set with six tubular fluorescent lamps (60cm with 18W and 120cm with 36W). Measurements were conducted using Spectroradiometer Ocean Optics HR 2000 with 4.7% uncertainty and a photometric bench to assess the spectral output. Additionally, UVA/B silicon detector and Luxmeter detector setups with uncertainties of 5.2% and 6%, respectively, were employed for irradiance and illuminance measurements of tubular LEDs and fluorescent lamps. Various parameters, including daylight factor ratio, UVA power to luminous flux (K) for tubular fluorescent lamps, spectral power distribution, and illumination levels were obtained. Integration between daylight and tubular LED lamps was also determined. The maximum detected value $0.013\,\mu W/lm$ is less than the safe limit for human health but still there are effects on human health if they use these types of lamps. Therefore, it is advisable to switch from tubular fluorescent lamps to tubular LEDs to mitigate the impact of UVA on human health and the environment.

Keywords: illuminance, daylight factor, spectral power distribution (SPD), UVA radiation, irradiance tubular LEDs lamp, tubular fluorescent lamp, uncertainty budget.

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1. INTRODUCTION

Light plays an important role in our body's optimal operation, and its influence extends to our mental well-being and mood. Studies show that a carefully designed visual environment can significantly increase student performance. [1, 2]. Before the advent of electric lighting in 1879, buildings relied on natural light. But as artificial lighting took over, concerns about design, energy, and the environment pushed for a hybrid approach, using both natural and artificial light to cut energy use [3]. Between 1945 and 1975, overlooking daylighting in favor of cheap fluorescent lamps led to poorly designed buildings compared to older ones [4-7]. Fluorescent lamps play an important role in both industrial and household lighting, representing a clear and straightforward method to achieve energy efficiency [8]. Energy conservation has become a pivotal aspect in the current century, aligning with the principles of environmental preservation, economic considerations, and advancements in science and technology [9]. Among the array of energy-saving products available, tubular fluorescent lamps stand out as noteworthy contributors. The functioning of fluorescent lamps involves an arc discharge through a combination of mercury and a rare gas, typically argon. The active gas, mercury, operates at a pressure of approximately 6-10 $\times 10^{-3}$ torr, while the buffer gas, a rare gas, maintains a pressure of around 3 torr. The discharge involves electrons and mercury ions as conducting species, generating excited mercury atoms that emit abundant photons at 253.7 and 185 nm UV wavelengths. These resonant radiations from the mercury atom stimulate the phosphor coating on the inner surface of the enclosing glass tube, causing it to fluoresce within the visible spectrum [10]. Presently, the preferred solution for enhancing lighting systems revolves around the adoption of Light-Emitting Diodes (LEDs). LEDs, which have been recognized for numerous years, operate based on electroluminescence, a process where light is generated

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through the flow of electrons. This phenomenon was first observed in 1907 by H.J. Round at Marconi Laboratories, who utilized a silicon carbide (SiC) crystal and a cat's-whisker detector for demonstration [11]. Most contemporary LED luminaires generate white light by employing phosphor-coated blue LEDs, or less commonly, by using various combinations of red, green, and blue (RGB) LEDs. While the performance of general-service LED lamps can vary significantly, ongoing technological advancements are consistently improving the technology, even as the cost per lumen decreases.

Multiple research studies have highlighted the superiority of daylight over artificial lighting concerning its impact on occupants within buildings. A survey conducted in England and New Zealand found that nearly all office workers (99%) prefer having windows in their workplaces, with 86% expressing a strong preference for daylight as the most desirable light source [12]. Studies have connected extended exposure to artificial light with health concerns, highlighting lower stress levels and discomfort in spaces primarily lit by natural light. Canadian university students echoed these sentiments, recognizing lighting's influence on health and valuing working in spaces filled with daylight. Consistently, research shows both students and teachers prefer well-lit classrooms with outdoor views, positively affecting attendance and performance. [13, 14]. Efficient use of daylight not only increases office occupants' moods but also decreases absenteeism, increases motivation, job satisfaction, and engagement. In Canadian elementary schools, classrooms with natural light saw fewer absences and improved student health compared to conventional lighting [13, 15, 16]. The quality of lighting in office spaces significantly affects workers' productivity, which is commonly measured by task completion speed, accuracy, and sustained effort [17]. Studies highlight a strong preference for windows in office settings. Multiple case studies reveal the positive impacts of enhanced lighting: renovations in various settings led to substantial productivity increases, decreased absenteeism, and lower energy costs. [18, 19]. Academic performance also benefits from daylight-integrated buildings, with increased attendance and significantly improved reading and math test scores for students [20]. Initial costs for building and hiring staff are much higher than operational, maintenance, and energy expenses. Implementing daylighting doesn't substantially raise construction or ongoing costs but notably reduces lighting energy use and cooling needs [21]. Schools and universities in Egypt spend a significant amount of money on energy for electric lighting. They receive a significant amount of daylight during school hours, but artificial lighting is still used for much of the day. To create a good lighting concept for a classroom, it is important to consider the different visual tasks that will be performed there and to design a system that is flexible and of high quality. Table-1 in the European standard EN 12464-1 outlines the lowest levels of light needed for different tasks and activities within school environments [22].

Table-1. Provides a summary of the activities conducted in a classroom and their respective lighting needs.

Task	The teacher	The student	Standard Illuminance	
			In the class	In general
1	Writing on blackboard	Reading on blackboard	500 lux (vertical)	200 lux
2	Talking to the students	Paying attention to the teacher	300 lux	300 lux
3	Showing a presentation (slides, PowerPoint, television program, etc.)	Looking at the screen	300/10 lux	10 lux
4	Paying attention to working students	Writing, reading, drawing, etc.	300 lux	300 lux
5	Coaching computer activities	Looking at the computer screen and the paper	50 lux	300 lux above the computer
6	Preparing lessons	Not present	300 lux	50 lux

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In order to maximize daylight utilization and cater to the diverse lighting needs of teachers, students, and various activities, the classroom has been segmented into three sections: a blackboard area, a window area, and a corridor area [23] and Figure-1 depicts these designs.

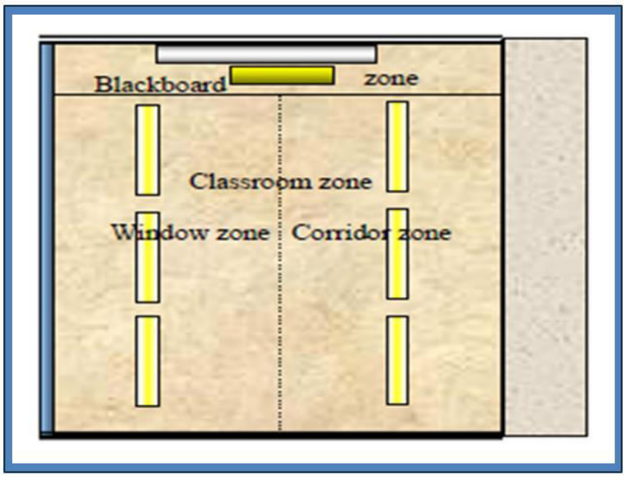

Figure-1. The specific zones of a classroom.

The illumination within an educational environment holds immense importance, being a crucial physical attribute. Insufficient lighting not only hinders clear visibility of materials but also has the potential to diminish engagement, particularly for students facing developmental challenges. Conversely, effective lighting yields significant positive effects on various aspects of successful learning, such as attention rates, working speed, productivity, and accuracy. If learning space has windows facing outside, it is advisable to maximize the entry of natural sunlight. To mitigate glare, consider employing shades or window decorations, especially during extended periods of screen or paper-focused activities by students. Figure-2 shows nine different designs windows of a classroom.

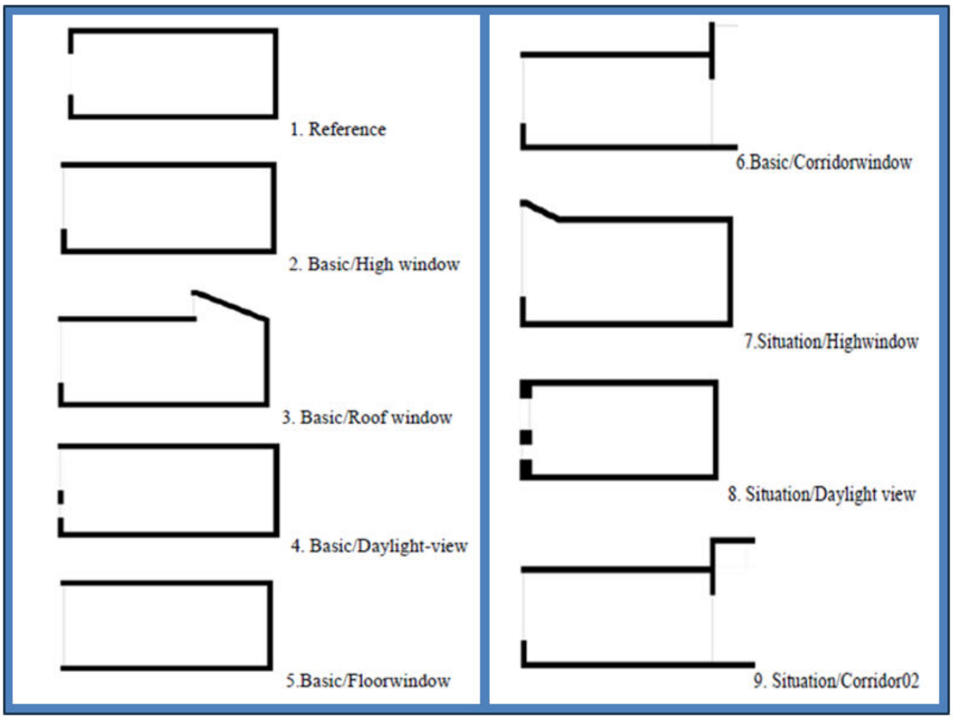

Figure-2. Nine different designs windows of a classroom.

Daylight factor (DF) is a measure of how much natural light is available inside a building compared to the amount of natural light available outside on a cloudy day. In other words, daylight factor is the ratio of the illuminance E_{indoor} of a horizontal plane at a given point inside a building due to the light received directly from an overcast sky of uniform luminance sky, to the illuminance $E_{outdoor}$ of the point due to the unobstructed sky [24].

$$DF = \frac{E_{indoor}}{E_{outdoor}} \times 100 \quad (1)$$

Spectral irradiance in UVA region is defined as the power of electromagnetic radiation per unit area in ($W/m^2/nm$). Ultraviolet radiation power per unit lumen output is defined as [25]

$$K = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda(\lambda)d\lambda}{k_m \int_{380nm}^{780nm} E_\lambda(\lambda)d\lambda V d\lambda} \quad (2)$$

In this study, different measurements are taken to gather various parameters, including the ratio of daylight factor, UVA power to luminous flux (K) for tubular fluorescent lamps, spectral power distribution of tubular LEDs and fluorescent lamps, and the illumination levels of tubular LEDs and fluorescent lamps. Also, determine the integration between daylight and tubular LEDs lamps.

2. EXPERIMENTAL SET UP AND METHODS

In the present research, the study of two groups of tubular lamps. The first group is six tubular LEDs lamps (60cm with 9Watt and 120cm with 18 Watt) and the other group six tubular fluorescent lamps (60cm with 18 Watt and 120cm with 36 Watt). Measuring a lamp's spectral power distribution (SPD) involves assessing light intensity across different wavelengths, crucial for understanding its color rendering, efficiency, and suitability for diverse applications. Spectral power distribution (SPD) measurement helps assess color accuracy, color temperature (warm or cool light), and energy efficiency of lamps. It's vital for lighting design, product development, and studying environmental impacts. Accurate SPD data is pivotal in choosing appropriate lighting solutions for varied applications, ensuring desired effects and performance in industries reliant on quality light sources. A spectroradiometer was employed to gauge the lamps' relative spectral output. The arrangement for assessing the spectral power distribution of the lamps, as depicted in Figure-3 involved direct measurement using the photometric bench and the Spectroradiometer ocean optics HR 2000 at NIS, yielding results with an uncertainty of 4.7% [26-28].

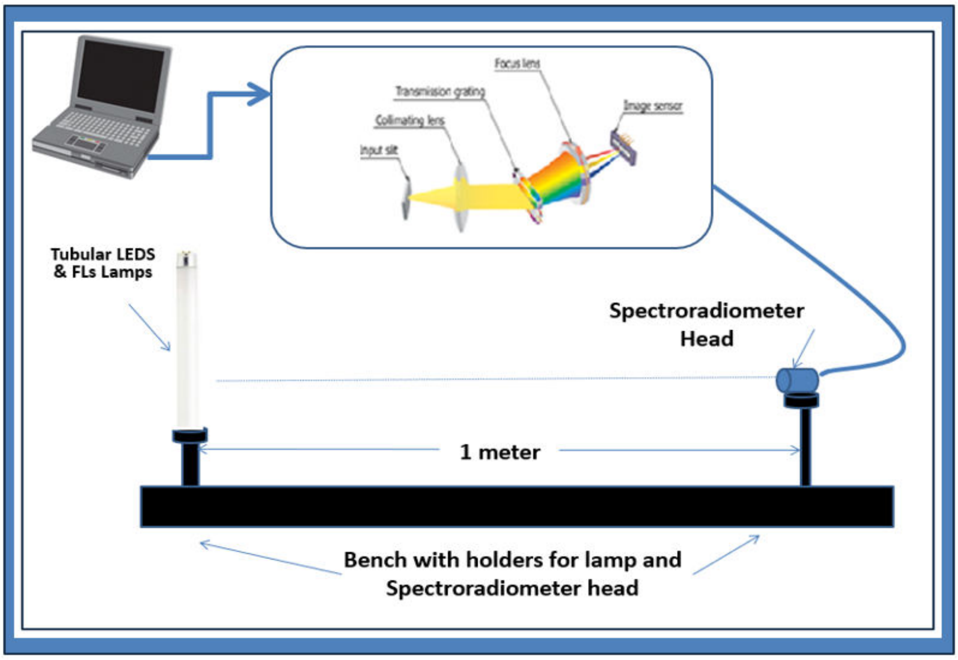

Figure-3. NIS setup for measuring the spectral power distribution.

The spectral power distribution of light was directly assessed using a photometric bench and spectroradiometer. The light under examination was directed into the spectroradiometer via an optical fiber, and its spectrum was transmitted to a computer through a USB port for data collection. Utilizing an optical fiber for light input allowed for adaptable measurement setups. The measurement method followed the CIE 63-1984 recommended by the International Electro technical Commission (IEC) [29]. Periodic calibration of the spectroradiometer was done using ASTM G138 standards method [30]. Spectroradiometers are highly accurate in assessing the spectral energy distribution of various light sources. Lamps being studied were individually positioned

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half a meter above the spectroradiometer, and after a five-minute interval, data for each lamp was recorded. All measurements took place in a controlled dark environment with regulated temperature $(25 \pm 1)^{o}C$ [26, 28, and 31].

Illuminance refers to the quantity of light landing on a surface, measured in lumens per square meter (lux). It holds significance across numerous fields like lighting design, photography, and vision science. The illuminance of each lamp is measured using a Luxmeter TM-201Lux as shown in Figure3. Measurements were performed in a conditioned dark room and maintaining the temperature at $(25 \pm 1)^{o}C$ at distance of 1 meter. Measurements were carried out on a photometric bench in a dark room. The Luxmeter was mounted on a translation stage and positioned at the same height as the tubular LEDs and fluorescent lamps on the optical bench as shown in Figure-4. Before taking measurements, each lamp was warmed up to 30 minutes. Measurements were repeated for each lamp and were finally averaged out and the uncertainty in irradiance measurements is calculated, yielding results with an uncertainty of 6%.

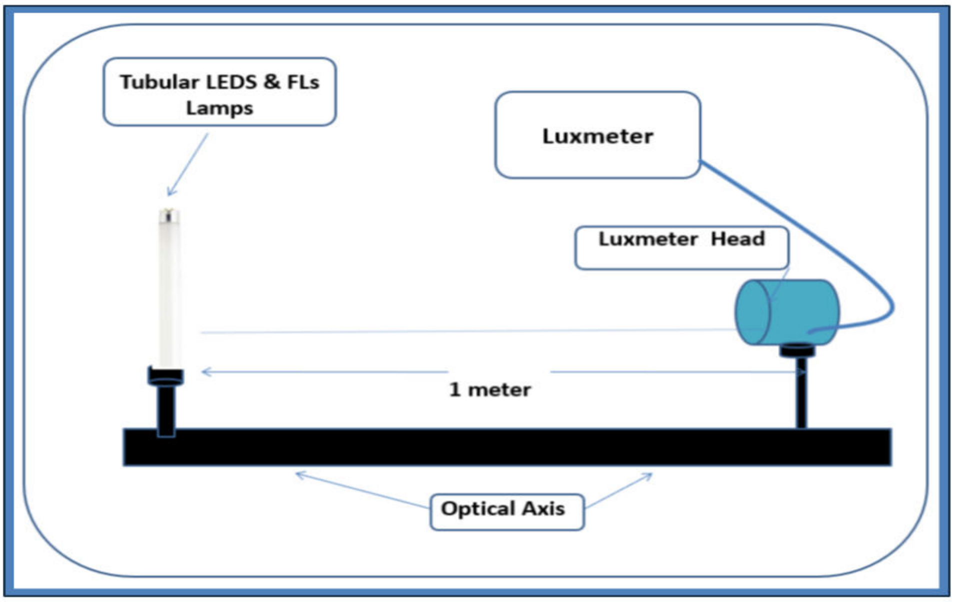

Figure-4. A setup for measuring illuminance for tubular LEDs and Fluorescent lamps.

Daylight factor (DF) is a measure of how much natural light is available inside a building compared to the amount of natural light available outside on a cloudy day. In other words, the daylight factor is the ratio of the illuminance E_{indoor} of a horizontal plane at a given point inside a building due to the light received directly from an overcast sky of uniform luminance sky to the illuminance $E_{outdoor}$ of the point due to the unobstructed sky [24]. We measured the illuminance E_{indoor} to the illuminance $E_{outdoor}$ of the point due to the unobstructed sky for building by using equation I to calculate the daylight factor using the Situation/Daylight view mode.

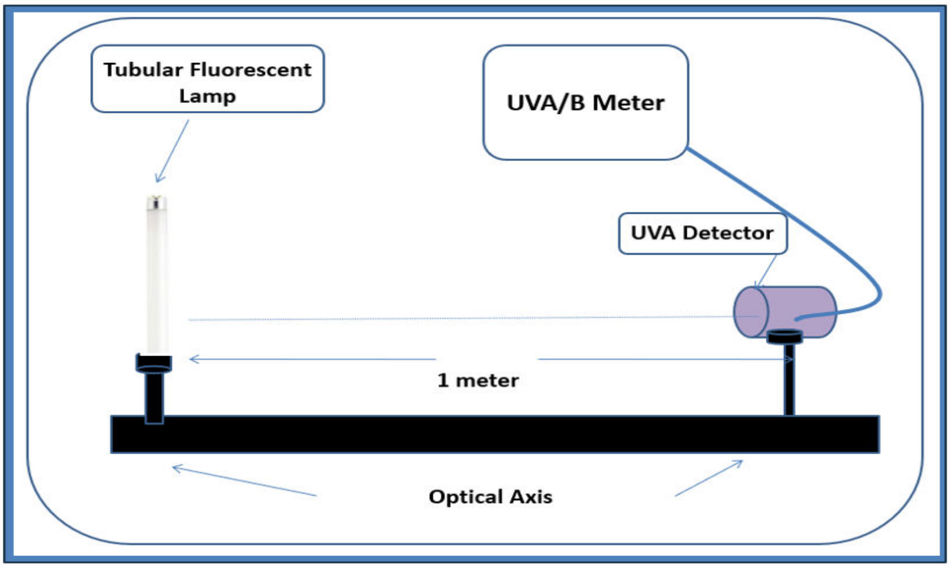

Figure-5. A setup for measuring UVA irradiance for tubular Fluorescent lamps.

Different parameters such as ultraviolet irradiance (UVA) and the ratio of UVA power to luminous flux (K) by using equation 2 are studied to dedicate the performance of tubular fluorescent lamps. Measurements were performed in a conditioned dark room with conditioned surfaces according to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommendations and maintaining the temperature at a distance of 1 meter. The photometric bench consists of Sper Scientific UVA/B Light Meter (Model 850009C) as shown in Figure-5 and calibrated at the National Institute of Standard and Technology (NIST), USA. The UVA detector was mounted on a translation stage and positioned at the same height as the tubular fluorescent lamps on the optical bench. Prior taking measurements, each tubular fluorescent lamp warmed up to 30 minutes. Measurements were repeated for each lamp and were finally averaged out and the uncertainty in irradiance measurements is calculated yielding results with an uncertainty of 5.2%.

3. RESULTS AND DISCUSSIONS

Figures 6 and 7 illustrate spectral power distribution (SPD) diagrams of tubular LED lamps and tubular FLs lamps across the visible spectrum (400 to 700 nanometers).

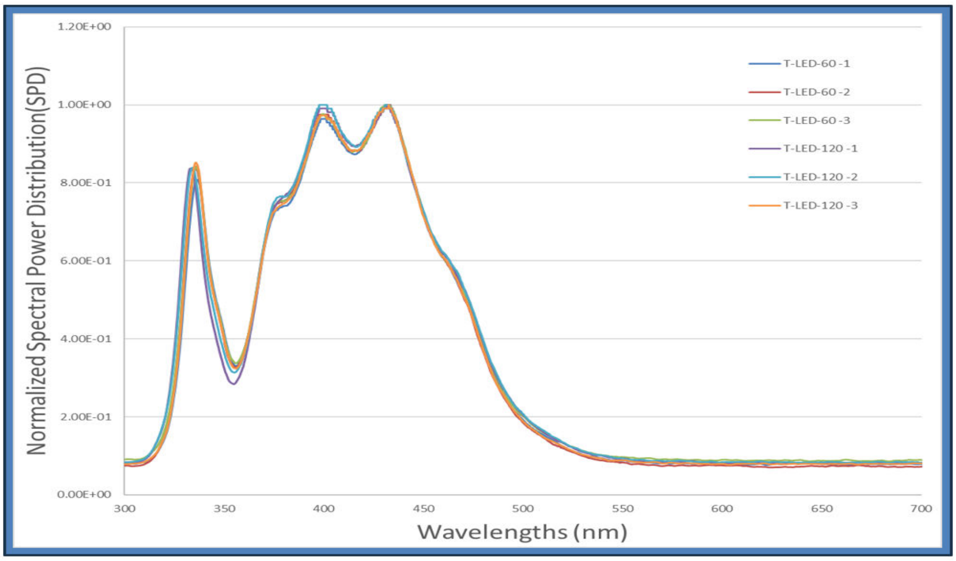

Figure-6. Spectral power distribution diagrams across the visible spectrum of tubular LEDs lamps.

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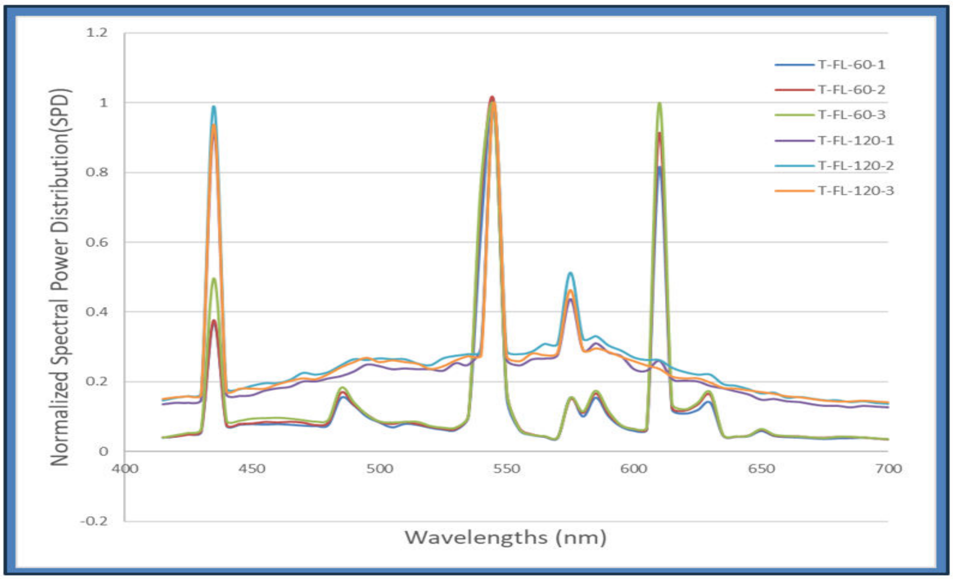

Figure-7. Spectral power distribution diagrams across the visible spectrum of tubular FLs lamps.

These diagrams depict how each lamp emits radiant power within the range perceived by the human eye. Comparing these SPD diagrams against the human response curve V(λ) reveals how each lamp's emitted light aligns with human visual perception. This comparison offers insights into the interaction between the radiant power emitted by each lamp and human visual sensitivity, aiding in understanding their spectral characteristics. Each lamp type showcases unique spectral distributions through varying peaks and patterns across the visible spectrum in the SPD diagrams. These distinctive peaks or patterns highlight the specific wavelengths at which each lamp emits light most prominently.

Overall, Figures 6 and 7 visually compare how these tubular LED lamps emit radiant power across the visible spectrum, allowing for a comprehensive analysis of their spectral characteristics and their relation to human visual sensitivity. Understanding these spectral power distributions assists in evaluating the lamps' suitability for diverse outdoor lighting applications, encompassing considerations like color rendering, energy efficiency, and visibility.

Figures 8 and 9 illustrate the illuminance emitted from the tubular LEDs and tubular fluorescent lamps. The highest illuminance value was emitted from the tubular fluorescent 120cm lamp while the lowest value was emitted from the tubular LEDs 60cm lamp. The illuminance levels measured using the Situation/Daylight view mode in the classroom. The highest illuminance value was recorded at 0.5 meters from the window, while the lowest value was observed at 5.5 meters from the window.

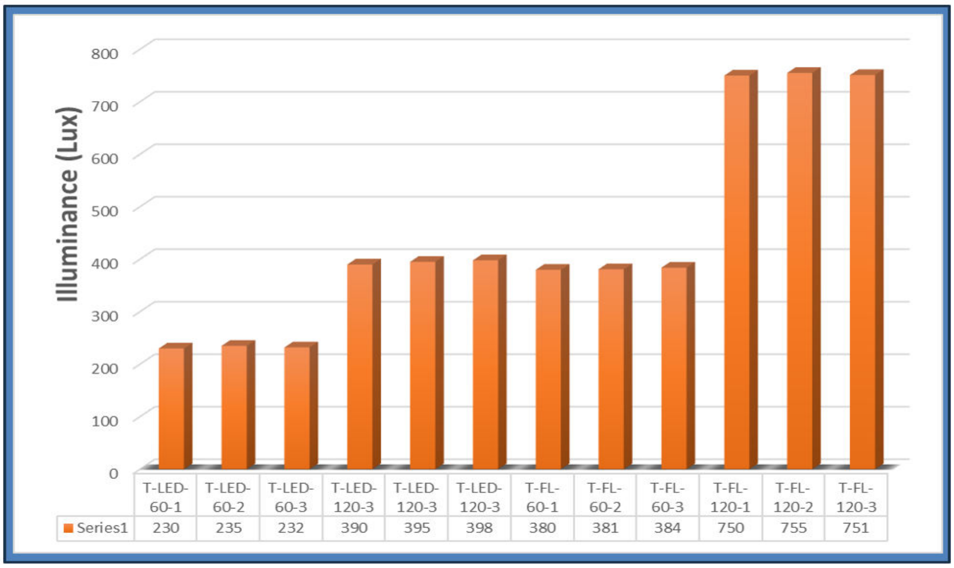

Figure-8. The Illuminance of tubular LEDs and tubular fluorescent lamps.

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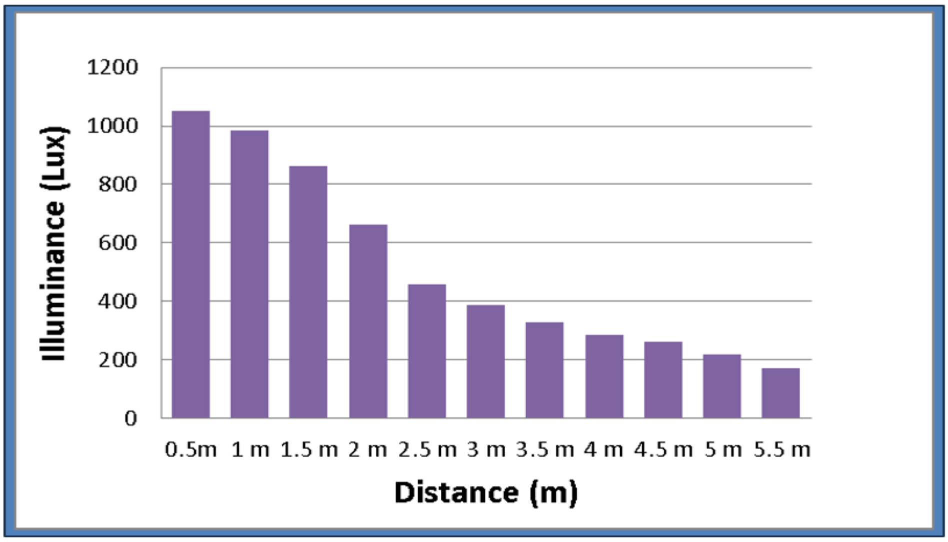

Figure-9. Illuminance distribution for the Situation/Daylight view mode.

Figure-10 illustrates the daylight Factor for the Situation/Daylight view mode by utilizing equation 1. It is determined by measuring the indoor illuminance (E_{indoor}) to the outdoor illuminance ($E_{outdoor}$) at the specific point, considering the unobstructed sky for the building. The maximum daylight factor was measured at a distance of 0.5 meters from the window, reaching 10.25%, whereas the minimum value was noted at a distance of 5.5 meters from the window, registering at 1.8%.

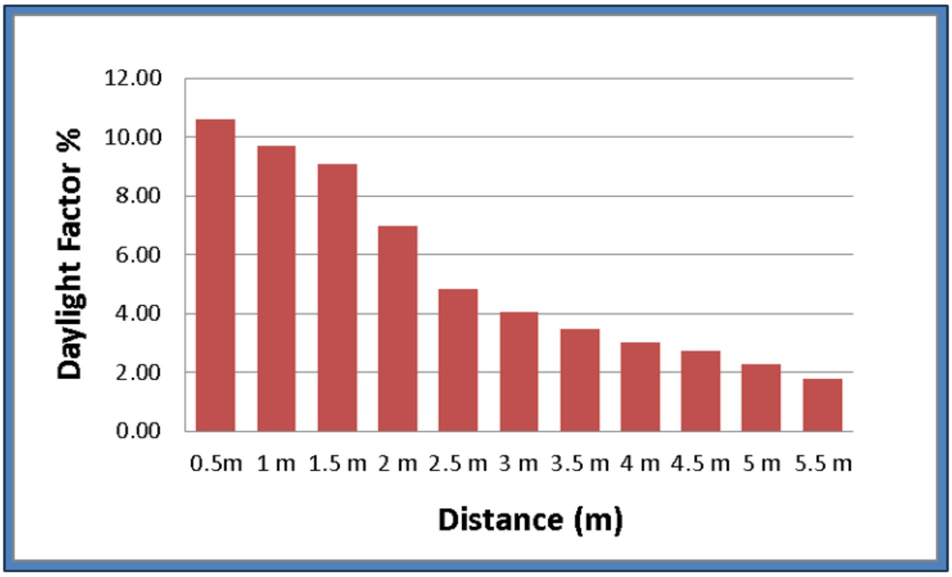

Figure-10. Daylight Factor for the Situation/Daylight view mode.

UVA irradiance to illuminance ratio (K), is of more interest for analyzing the tubular fluorescent lamps radiation characteristics. The amount of illuminance for the tubular fluorescent lamps is measured at 1 meter distance. Ratio K which is UVA absolute irradiance levels per illuminance values for the tubular fluorescent lamps. Figure-11 shows the histogram for comparison of UVA absolute irradiance levels per illuminance values (K) for the tubular fluorescent lamps at 1 meter distance. The values of (K) at 1 meter distance for the tubular fluorescent lamps varies from $0.0079\,\mu W / lm$ to $0.013\,\mu W / lm$. The maximum detected value $0.013\,\mu W / lm$ is less than the safe limit for human health.

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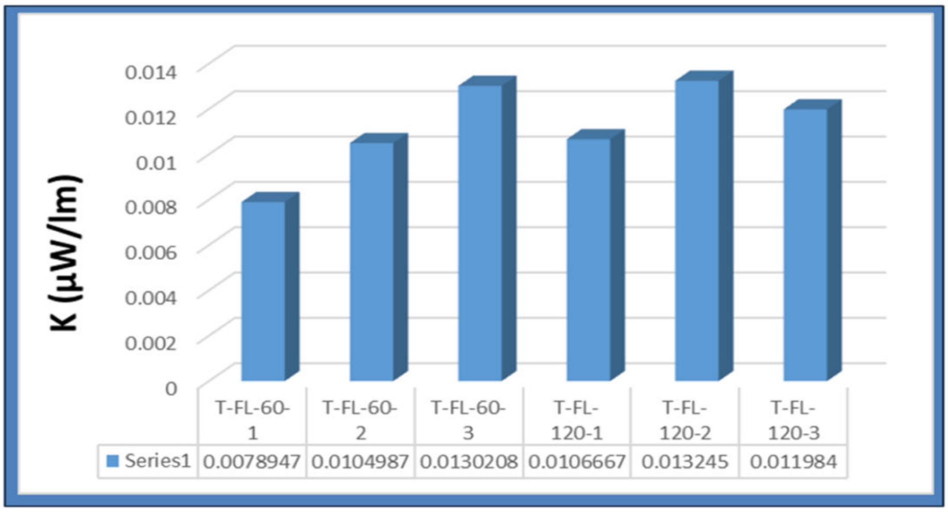

Figure-11. UVA absolute irradiance levels per illuminance values (K) for tubular fluorescent lamps using a calibrated UVA radiometer and luxmeter at 1 meter.

4. UNCERTAINTY ANALYSIS

Evaluation of the uncertainty is done by the Guide to the expression of uncertainty in Measurement (GUM) method. This method is adopted and described in details by International Organization for Standardization (ISO). The standard uncertainty $u(x_i)$ to be associated with input quantity *xi* is the estimated standard deviation of the mean [32, 33].

$$u(x_i) = s(\bar{X}) = \left(\frac{1}{n(n-1)} \sum_{k=1}^{n} (X_{i,k} - \bar{X})^2 \right)^{1/2} \tag{3}$$

The combined standard uncertainty *uc*(*y*) is obtained by combining the individual standard uncertainties u_i these can be evaluated as Type A and Type B. That is,

$$u_c^2(y) = \sum_{i=1}^{N} (\frac{\partial f}{\partial x_i})^2 u^2(x_i) \tag{4}$$

Uncertainty model used for the determination of the UVA irradiance $E_{UVA}(\lambda)$ is [34]:

$$E_{UVA}(\lambda) = E_S(\lambda) + \delta E_l + \delta E_r \tag{5}$$

where, $E_S(\lambda)$ = uncertainty due to reference spectral irradiance UVA standard radiometer (obtained from the calibration certificate).

δE_l = uncertainty due to the distance effect on the irradiance measurements (calculated by using the inverse square law).

δE_r = uncertainty due to repeatability of the measurements (standard deviation of repeated 5 times).

The uncertainty must be quoted whenever the results of a measurement are reported, it tells us about the precision with which the measurements were made. The uncertainty budget of the UVA irradiance, spectral power distribution, and illuminance measurements are shown respectively in Table-2, Table-3, and Table-4 with a confidence level of 95% (coverage factor *k* = 2).

Table-2. Estimated uncertainty budget of UVA irradiance for tubular fluorescent lamps.

Uncertainty Component	Relative Standard Uncertainty (%)
Irradiance responsivity calibration of standard radiometer	5.2
Distance measurements	0.015
Repeatability	0.021
Relative Expanded Uncertainty (*k*=2)	10.4

Table-3. Estimated uncertainty of spectral power distribution measurements for tubular LEDs and tubular fluorescent lamps.

Uncertainty Component	Relative Standard Uncertainty (%)
Calibration of spectroradiometer	4.7
Distance measurements	0.016
Lamp Regulation	0.001
Repeatability	0.024
Relative Expanded Uncertainty (*k*=2)	9.4

Table-4. Estimated uncertainty budget of illuminance measurements for tubular LEDs and tubular fluorescent lamps.

Uncertainty Component	Relative Standard Uncertainty (%)
Illuminance responsivity calibration of standard photometer	6
Distance measurements	0.014
Repeatability	0.022
Relative Expanded Uncertainty (*k*=2)	12

5. CONCLUSIONS

The comfort of illumination plays an important role in influencing our task performance within enclosed areas. Various attributes of lighting sources can impact the overall quality of illumination. In this research, two groups of tubular lamps were studied. The first group is six tubular LED lamps (60cm with 9 watts and 120cm with 18 Watt) and the other group has six tubular fluorescent lamps (60cm with 18 Watt and 120cm with 36 Watt). The tubular LEDs lamps can be utilized both in residential settings and office spaces more than the tubular fluorescent lamps. A set up based on Spectroradiometer Ocean Optics HR 2000 with an uncertainty 4.7% and photometric bench was used to measure the lamps' spectral output for tubular LEDs and fluorescent lamps. A second set up based on UVA/B silicon detector with an uncertainty 5.2% and optical bench for irradiance measurements in UVA region. A third setup up based on Luxmeter detector with an uncertainty 6% and optical bench for measuring the illuminance of tubular LEDs and fluorescent lamps. Various parameters are obtained from measurements such as the ratio of daylight factor, UVA power to luminous flux (K) for tubular fluorescent lamps, spectral power distribution of the tubular LEDs and fluorescent lamps, and illumination levels of the tubular LEDs and fluorescent lamps. Also, determine the integration between daylight and tubular LEDs lamps. The illuminance values show that the group of tubular fluorescent lamps is higher in illuminance level than the group of the tubular LEDs lamps. But the illuminance per electrical wattages for the tubular LEDs lamps is higher than the tubular fluorescent lamps. This is means that the tubular LEDs lamps is more savers in energy than the tubular fluorescent lamps. On the other hand, tubular LEDs are environmentally friendly due to their mercury-free composition, offering directional lighting that minimizes wastage and enhances efficiency by about 40% compared to fluorescent lamps. They produce high-quality light with varied color temperatures, eliminating flickering issues that can cause discomfort. Additionally, their extended lifespan makes tubular LEDs a preferred and durable lighting option. The daylight measured using Luxmeter TM-201Lux by measuring the illuminance in and out a classroom. According to the results, the tubular fluorescent lamp of 120cm emitted the highest illuminance, whereas the tubular LEDs lamp of 60cm yielded the lowest value. The illuminance measurements were taken in the classroom using the Situation/Daylight view mode. The greatest illuminance was noted at a distance of 0.5 meters from the window, while the lowest value was observed at a distance of 5.5 meters from the window. The Daylight Factor for the Situation/Daylight view mode was calculated using equation (1). This factor is determined by assessing the indoor illuminance (E_{indoor}) relative to the outdoor illuminance ($E_{outdoor}$) at a specific location, taking into account the unobstructed sky around the building. The highest recorded Daylight Factor was 10.5%, observed at a distance of 0.5 meters from the window, while the lowest value was 1.8%, observed at a distance of 5.5 meters from the window. In Figure-10, the daylight factor reached its highest point, reaching 10.25%, when measured at proximity of 0.5 meters from the window. Conversely, the lowest recorded value, at 1.8%, was observed at a distance of 5.5 meters from the window. To ensure adequate illumination in the classroom, it is essential to address the reduction in illumination from 3 meters to 5.5 meters by integrating artificial lighting. This integration involves the use of either tubular fluorescent lamps or tubular LED lamps. UVA absolute irradiance levels per illuminance values (K) for the tubular fluorescent lamps at 1 meter distance. The values of (K) at 1 meter distance for the tubular fluorescent lamps varies from $0.0079\,\mu W/lm$ to $0.013\,\mu W/lm$. The maximum detected value $0.013\,\mu W/lm$ is less than the safe limit for human health but still there are effects on the human health if they use these type of lamps. So, it is preferable to replace tubular fluorescent lamps to tubular LEDs lamps to prevent the effects of UVA on the human health and environment. Data analysis was performed and Uncertainty model includes all parameters accompanied with the measurements studied. The accompanied uncertainty in the absolute UVA irradiance measurements (10.4 %), spectral power distribution (9.4 %), and in the illuminance measurements (12%) are calculated respectively in Table-2, Table-3, and Table-4 with confidence level 95% (k = 2).

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