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MORALITY BEFORE KNOWLEDGE

How dark is the night sky? A preliminary assessment of light pollution and astrotourism potential

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ABSTRACT

Background: Light pollution degrades night sky quality and may limit opportunities for astronomy-based tourism (astrotourism). Although Batu City has astrotourism potential, information on its night sky quality remains limited. This study characterized night sky brightness in Batu District, compared field measurements with Light Pollution Map (LPM) data, and evaluated its implications for astrotourism. **Methods**: Night sky brightness was measured at six observation sites in Batu District using a D.I.Y-CJ'01 photometer equipped with a TSL237 sensor. Measurements were conducted at the zenith under suitable weather conditions for 2–3 minutes at each site. Data were expressed in mag/arcsec^2, classified using the Bortle Scale, and compared with LPM data. **Findings:** The average night sky brightness ranged from 11.81 to 18.10 mag/arcsec^2. The highest value occurred in a peripheral residential area and the lowest in a commercial area. Most sites were classified as Bortle Class VIII–IX, indicating city to inner-city sky conditions. LPM estimated darker skies (19.79–20.46 mag/arcsec^2; Bortle Class IV–V) than field measurements, although both showed decreasing sky quality with increasing urban activity and artificial lighting. However, the findings should be interpreted with caution because of methodological limitations, including measurement duration, technical limitations of the instrument, differences between photometer and LPM measurements, and uncontrolled environmental factors. **Conclusion**: The results indicate substantial light pollution in Batu District, making most surveyed locations less suitable for astrotourism. However, variations in sky brightness suggest that other areas of Batu City may still support astrotourism. These findings are expected to guide regional planners and tourism stakeholders in formulating artificial lighting management policies that support the sustainable development of astrotourism in Batu City. **Novelty/Originality of this article:** This study provides a preliminary field-based assessment of night sky brightness, light pollution, and astrotourism potential in Batu District through direct photometric measurements and LPM comparison.

KEYWORDS: astrotourism; Bortle's Scale; light pollution; night sky brightness.

1. Introduction

In the field of astronomy, the luminance of the night sky plays a crucial role in determining how well celestial bodies can be seen, which makes assessing its brightness vital for astronomical studies and evaluating sky quality (Barentine, 2022; Wesołowski, 2023). Celestial objects can be clearly observed if the night sky is clear. The brightness of the night sky is strongly influenced by meteorological conditions, particularly the extent of cloud cover, which plays a major role in scattering natural and artificial light and

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consequently altering night sky brightness (Martínez-Martín et al., 2023; Luciano Massetti et al., 2023). The luminosity of the night sky is shaped by a mix of both natural and human-made elements, such as the locations of the Moon and Sun, weather circumstances (for instance, airglow and light scattering), the impact of natural sources of celestial illumination, and the excess light caused by human activities (Barentine, 2022; Green et al., 2022).

Light pollution is a major factor affecting sky brightness and recognized as a condition caused by excessive light levels, causing discomfort. Light pollution refers to the presence of artificial light at night (ALAN) at inappropriate times, intensities, amounts, or spectral characteristics that alter the natural darkness of the night environment (Bará & Falchi, 2023; Machnowska & Skwarlo-Sonta, 2026). According to the International Dark Sky Association, the main forms of light pollution include glare, skyglow, light trespass, and light clutter. Among these, skyglow is the primary form affecting night sky brightness because artificial light scattered in the atmosphere reduces the visibility of celestial objects. The occurrence and intensity of these forms of light pollution are strongly influenced by urban development and expansion.

Urban expansion is closely linked to increased light pollution. Urban expansion is occurring in several countries, including Indonesia (Yan & Tan, 2023). Currently, Indonesia is experiencing quite rapid progress in terms of development, particularly in the clearing of new land and the construction of buildings. This is evident in the increasing number of people in cities and regions competing to build high-rise buildings (Putraga et al., 2023). One of the cities experiencing urban expansion is Batu City. Batu City is the youngest autonomous city in East Java Province. With a total area of 15,137 hectares, Batu City previously held the status of an Administrative City, showing rapid development, particularly in the implementation of division and demographic development. Batu City consists of three sub-districts (Junrejo Sub-district, Batu Sub-district, and Bumiaji Sub-district), 19 villages, and 4 urban villages (Putra et al., 2021).

Batu City is considered one of the successful urban developments in building its regional image and attracting investment to stimulate the local economy through Kota Wisata Batu (KWB) concept. This success is reflected in the development of tourism businesses in Batu City. As a tourist city, Batu City experienced a significant increase in tourist arrivals, reaching 30.4% in 2019. This increase ultimately drove the growth of tourist attractions, restaurants, and accommodations. Furthermore, the number of hotels in Batu City increased by 45.27% in 2020 (Witjaksono et al., 2023). This situation ultimately led to an increase in built-up land and land conversion that deviated from its designated function. Furthermore, the increasing tourism development in Batu City has also caused anxiety among local residents. This is due to the emergence of various problems that have developed alongside tourism development in Batu City, ranging from economic, socio-cultural, and environmental issues (Putra et al., 2021).

Environmental issues in Batu City, frequently highlighted in various media outlets, relate to the increased risk of flooding and landslides resulting from land conversion. On the other hand, the impacts of land conversion can also give rise to environmental problems that have received little attention. One such issue is light pollution. As a tourism-oriented city, Batu City has made efforts to beautify certain iconic areas to attract tourists. One of the efforts undertaken by Batu City is implementing urban lighting design. The concept of urban lighting design is defined as architectural lighting that can enhance and strengthen a city's image by illuminating specific areas through the use of dynamic and attractive lighting. Attractive and dynamic artificial lighting is beginning to be applied to commercial buildings with the aim of strengthening the image of urban cities. Ideally, the concept of urban lighting design should not only produce attractive and dynamic lighting, but also fulfill the aspects of security, safety, orientation, and visual comfort to accommodate the needs of users with different backgrounds and behaviors, ensuring a comfortable and safe visual experience (Jedon et al., 2023; Trop et al., 2023). Unfortunately, the use of dynamic and attractive lighting can cause problems when overused and begin to disrupt surrounding areas. This increased lighting situation is highly likely to occur in Batu City.

The potential for increased lighting in Batu City as a cause of light pollution needs to be proven with quantitative data. Light pollution in a location can be determined by measuring the brightness of the night sky using a photometer (Putraga et al., 2023). One type of photometer that can measure the brightness of the night sky is the Sky Quality Meter (SQM). An SQM is an instrument used to measure the luminosity of the night sky anywhere and at any time. The output of an SQM is a value of sky brightness in magnitudes per square arc second (MPSAS). A high value indicates a darker sky and high sky quality (Balafoutis et al., 2025).

Several previous studies have demonstrated the phenomenon of light pollution occurring in almost every region, especially in urban areas. The results of research conducted abroad, namely in the city of Rzeszów (Poland), showed an increase in the brightness of the night sky surface reviewed in the period 2015, 2018, and 2021. The brightness of the night sky, which in 2015 was in class IV on the Bortle's scale (20.30 mag/arsec2-21.30 mag/arsec2), experienced an increase to class IX in 2021 (<18.00 mag/arsec2). These results indicate the development of light pollution occurring in the city (Wesołowski, 2023). In Indonesia, pollution research has also been conducted in several regions. DKI Jakarta, particularly the Taman Ismail Marzuki Planetarium and Observatory, has been shown to have high levels of light pollution (Bustari et al., 2019). Other studies also show that big cities like Medan have high levels of light pollution and this increases throughout the year (Putraga et al., 2023; Rakhmadi et al., 2020).

Beyond its environmental consequences, light pollution has emerged as a critical factor in tourism planning, particularly in the context of dark-sky tourism and astrotourism. Dark skies are increasingly recognized as valuable natural resources that can strengthen destination differentiation and place branding by emphasizing the authenticity of the natural nighttime environment (Alva et al., 2025; Ndubisi & Nair, 2023). In this regard, documented night sky quality data provide a scientific basis for astrotourism development and may support international recognition, such as International Dark Sky Park or Dark Sky Reserve status, thereby enhancing destination attractiveness (Barentine, 2022; International Dark Sky Association, 2018). For Batu City, which already positions itself as a nature-based tourism destination, understanding the current state of light pollution is therefore not only an environmental concern but also a strategic consideration for sustainable tourism development and long-term destination competitiveness.

Although several studies have been conducted on light pollution measurements both in Indonesia and abroad, empirical data on night sky brightness in Batu City remains remains unavailable. Consequently, there is limited understanding of the actual night sky conditions, the consistency between field measurements and Light Pollution Map (LPM) estimates, and the implications of these conditions for astrotourism development. As a rapidly developing tourist city, Batu City is likely to experience increasing nighttime artificial lighting that may intensify light pollution. At the same time, its highland setting offers favorable conditions for astrotourism based on night sky observation. However, this potential may decline if artificial lighting is not properly managed. To address this gap, this study aims to characterize the brightness of the night sky at several locations in Batu District, compare field measurements with data from the light pollution map, and analyze the implications of the measured light pollution levels on the potential for astrotourism development in Batu City. The findings are expected to provide an evidence base for managing artificial lighting and supporting sustainable astrotourism development while preserving night sky quality in Batu City.

2. Methods

2.1 Research location

This research was conducted in Batu City, East Java, Indonesia. Batu City is a tourist city located in a mountainous area with an altitude of approximately 700-1,700 m above sea level. Batu City consists of three sub-districts, namely Junrejo District, Batu District, and

Bumiaji District. However, the focus location chosen in this study is Batu District. The selection of Batu District as the main focus of the research location is based on the consideration that the location represents the urban and tourism center so that artificial lighting activities are relatively concentrated. Six observation locations to illustrate the conditions of different areas, ranging from suburban/rural residential areas to areas closer to the center of urban activity.

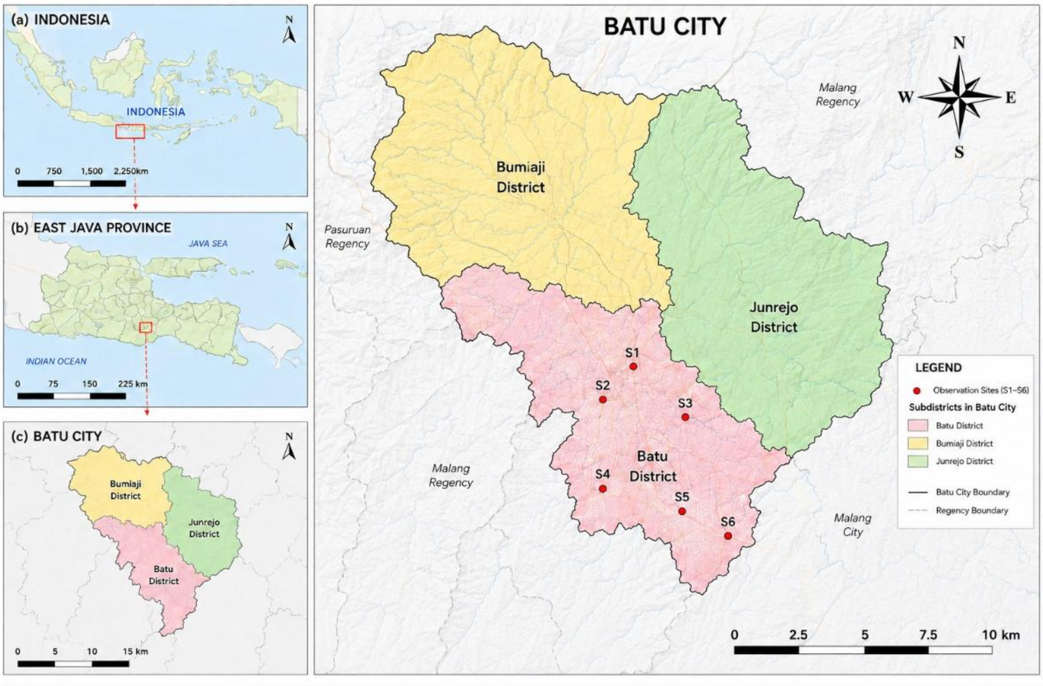

Fig. 1. Research location

There are several criteria used in determining the six observation locations. These criteria are: (1) variations in land use characteristics, ranging from suburban residential areas to urban activity centers; (2) openness of the area to the zenith sky without significant obstructions from trees or buildings; (3) accessibility of the location that allows measurements without disturbing public order and safety; and (4) adequate representation of spatial distribution to describe the gradient of light pollution from the outskirts to the city center. The geographic coordinates and descriptions of each observation location are presented in Figure 1 and Table 1.

Table 1. Observation sited

Site Code	Observation Sited	Latitude	Longitude	Description
S1	Kampung Temas (Wukir VI C Street)	7°52'42.6"S	112°32'30.2"E	Peripheral residential area
S2	Koperasi Desa Merah Putih Temas (Wukir Street)	7°52'35.7"S	112°32'29.0"E	Semi-urban residential area
S3	Sendratari Arjuna Wiwaha	7°52'20.2"S	112°32'12.3"E	Residential area near the city center
S4	Lippo Plaza Batu (Diponegoro Street)	7°52'42.9"S	112°32'2.8"E	Commercial area
S5	Batu City Square (Agus Salim Street)	7°52'17.6"S	112°31'39.3"E	Urban public space
S6	Among Tani City Hall (Panglima Sudirman Street)	7°52'0.2"S	112°30'47.2"E	Government area

2.2 Research instruments

The instrument used in this study to measure the brightness of the night sky was the D.I.Y-CJ'01 Photometer. A photometer is a tool used to measure illumination or lighting (Haridy, 2024). In general, photometers are usually integrated into instruments that detect the intensity of scattered, absorbed, and fluorescent light. Photometers measure the brightness of the night sky in magnitudes per square arcsecond (mag/arcsec^2), where higher values indicate darker skies and lower levels of light pollution. The D.I.Y-CJ'01 Photometer integrates the TSL237 sensor using an Arduino Nano microcontroller. The photometer is also equipped with an LCD screen to display measurements and a time display with a real-time clock (RTC) module and a data logger to store measurement results, including internal resources, all packaged in a single device. The D.I.Y-CJ'01 Photometer used in the study can be seen in Figure 2.

Fig. 2. DIY-CJ'01 Photometer

Before being used in this study, the DIY-CJ'01 Photometer underwent testing and calibration to ensure that the instrument could be used to reliably measure night sky quality. The instrument was tested by comparing its night sky quality measurements with those from the Sky Quality Meter (SQM) Unihedron photometer, a standardized commercial instrument. Functionally, the instrument testing results showed that the DIY-CJ'01 Photometer is well-suited for measuring night sky quality. Under identical measurement conditions, both instruments produced night sky brightness values that were very close, with an average difference of 0.01–0.02 mag/arcsec^2. The measurement results obtained from the DIY-CJ'01 Photometer also show data patterns that are similar or comparable to those from the SQM Unihedron (Asmoro et al., 2022). Thus, the DIY-CJ'01 photometer is deemed suitable for measuring night sky quality in this study.

2.3 Data collection

Data collection was conducted at six locations in Batu District. Data collection took place at night in an open location in the Zenith area, specifically in the sky above the head. Data collection took place on March 17, 2026, taking several factors into account. Several requirements were met during the data collection process, including the absence of heavy clouds or rain, the absence of obstructions from trees or buildings, direct exposure to artificial light, and the absence of obstructions to public access, such as in the middle of a road. In addition, the timing of the observation also took into account the current phase of

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the moon. Data collection coincided with the waning crescent phase, when 3.6% of the moon's visible surface was illuminated. Since this phase is close to the new moon, the effect of moonlight on the brightness of the night sky during the observation night can be considered minimal and unlikely to significantly affect the measurement results.

Geographic coordinates were recorded at each data collection location using a Global Positioning System (GPS). Data collection for each location lasted 2-3 minutes on a single night. Data collection over a single night was determined based on practical considerations to cover several observation sites with diverse spatial characteristics during a single night of observation, following a spatial survey approach that measures night sky brightness at multiple locations during a single observation session to map the spatial distribution of light pollution in similar studies (Karpińska & Kunz, 2022). The data collection duration of 2–3 minutes per location was chosen because this study is a preliminary assessment aimed at obtaining an initial picture of night sky brightness at various locations with different characteristics during a single night of observation. However, we recognize that this brief measurement duration cannot capture temporal variability over the course of a single night.

The collection of measurement data in this study could potentially be influenced by several factors. These factors include variations in atmospheric conditions, changes in local weather during observations, the presence of artificial light sources near the observation site, and temporal variations in sky conditions. These factors were minimized by conducting measurements in accordance with the criteria described earlier. Nevertheless, some natural factors such as variations in atmospheric airglow and changes in atmospheric conditions that were not specifically monitored during the observations may still introduce uncertainty into the measurement results. The night sky brightness measurements for each location were then organized to facilitate further data analysis.

2.4 Data analysis

In this study, the main variable measured is the brightness level of the night sky expressed in units of magnitude per arc second squared (mag/arcsec^2) or can be expressed in MPSAS. The MPSAS value data collected using the D.I.Y CJ'01 photometer was then analyzed descriptively by calculating the minimum value, maximum value, and average value to determine the brightness level of the night sky at each observation location point. The analysis was conducted to identify variations in night sky quality resulting from differences in environmental characteristics and human activity around the observation location. Higher night sky brightness values indicate darker skies and lower levels of light pollution. Conversely, lower night sky brightness values indicate brighter skies and higher levels of light pollution.

Table 2. Bortle's classification

Class	Type of Sky	Values SQM (mag/arcsec^2)	The Color of The Sky
I	Excellent dark-sky site	21.75-22.00	Black
II	Typical a truly dark site	21.60-21.75	Gray
III	Rural sky	21.30-21.60	Blue
IV	Brighter rural/suburban transition sky	20.30-21.30	Green/yellow
V	Suburban sky	19.25-20.30	Orange
VI	Bright suburban sky	18.50-19.25	Red
VII	Suburban/urban transition	18.00-18.50	Red
VIII	City sky	<18.00	White
IX	Inner-city sky	<18.00	White

(Bortle, 2001)

The measurement results are then interpreted using an astronomical concept in the form of the Bortle Dark-Sky Scale, which groups the quality of the night sky based on the level of darkness of the sky and the visibility of astronomical objects. The average MPSAS value at each location is grouped according to the Bortle's Classification criteria as in Table

2. The distinction between Bortle Classes VIII and IX cannot be made using MPSAS alone because the original Bortle Scale incorporates multiple observational criteria, including limiting stellar magnitude, Milky Way visibility, zodiacal light, and other visual characteristics of the night sky. MPSAS therefore serves only as an approximate indicator of the corresponding Bortle class. The interpretation results are also used to describe the light pollution conditions at each observation location point and are used to provide an initial assessment of the potential for developing astrotourism at the observation location.

Data analysis was also conducted by comparing field measurements with data from the light pollution map. The comparison was made between the MPSAS values and Bortle classes generated by both data sources. The data comparison was conducted to determine the level of agreement between the night sky brightness distribution patterns. The absolute difference (Δ MPSAS) between field measurements and LPM estimates was calculated for each observation site to quantify the magnitude of the discrepancy between the two data sources. Furthermore, a Spearman rank correlation analysis was performed to assess whether both datasets reflect a consistent spatial pattern of night sky brightness variation across observation sites, given the small sample size ($n = 6$) and the ordinal nature of the Bortle classification. The data comparison results were also used to provide an overview of the consistency between direct field measurements and satellite imagery-based estimates in representing light pollution conditions in Batu District.

2.5 Research framework

This research framework consists of six stages, including: (1) problem identification and literature review, (2) research objectives, (3) study area selection, (4) data collection, (5) data analysis, and (6) conclusion. Figure 3 shows the research framework used in this study. The research began with problem identification and a comprehensive literature review related to night sky brightness, light pollution, and astrotourism development. These stages were carried out to build a theoretical foundation, understand the development of previous research, and identify gaps and research urgency related to night sky brightness, light pollution, and astrotourism development in Batu City, which until now have been relatively rarely studied. At this stage, appropriate parameters and methods for assessing the quality of the night sky were also determined.

The results of the first stage were then used to formulate research objectives that would guide the research process. At this stage, three main research focuses were established: determining the brightness characteristics of the night sky at the observation location, comparing field measurements with light pollution map data, and analyzing the implications of light pollution levels on the potential for astrotourism development in Batu City. The next step was determining the research location. The observation location was selected in Batu District, taking into account variations in environmental characteristics and levels of human activity. Batu District was chosen because it is the center of tourism activity in Batu City, a major tourist destination. In this stage, six observation locations were determined to illustrate the different conditions of the region, ranging from suburban/rural residential areas to areas closer to urban centers. This way, the varying effects of artificial lighting on night sky quality can be observed.

The fourth stage is data collection to measure the brightness of the night sky. Measurements are conducted under favorable weather conditions, with observations directed toward the zenith. In addition to field measurements, estimated night sky brightness data from light pollution maps is also collected for comparative analysis.

The fifth stage is data analysis and interpretation to evaluate light pollution conditions and assess night sky quality. Field measurement results are then compared with data from the light pollution map to evaluate the suitability of the night sky brightness distribution patterns obtained from both data sources. The analysis results are also used to assess light pollution conditions and evaluate astrotourism development at the research site. The final stage is drawing conclusions and identifying research implications. Conclusions are based on the data analysis conducted to provide an overview of night sky conditions and light pollution in Batu District, as well as their implications for the potential for future astrotourism development.

3. Results and Discussion

3.1 Characteristics of night sky brightness at observation locations

The light pollution conditions in this study were determined by collecting data through night sky brightness measurements at six locations representing different regional characteristics, ranging from residential or rural areas to urban activity centers. The night sky brightness values measured using a photometer are expressed in mag/arcsec^2 (MPSAS). The higher the MPSAS value, the darker the sky and the lower the level of light pollution (Shariff et al., 2020). The measurement results data at each observation location are presented in Table 3.

Table 3. Night sky brightness data and its classification based on the bortle scale

Site Code	MPSAS Min (mag/arcsec^2)	MPSAS Max (mag/arcsec^2)	MPSAS Avg (mag/arcsec^2)	Bortle's Class	Type of Sky
S1	17.91	18.30	18.10	VII	Suburban/urban transition
S2	17.60	17.65	17.63	VIII-IX	City sky/Inner-city sky
S3	15.84	15.94	15.90	VIII-IX	City sky/Inner-city sky
S4	11.37	12.11	11.81	VIII-IX	City sky/Inner-city sky
S5	14.80	15.25	15.04	VIII-IX	City sky/Inner-city sky
S6	11.70	12.91	12.48	VIII-IX	City sky/Inner-city sky

Based on the data in Table 3, it can be seen that the results of the measurements of the average value of the night sky brightness at six different locations are in the range of 11.81-18.10 mag/arcsec^2. The highest average value of the night sky brightness was found in Kampung Temas (S1), namely 18.10 mag/arcsec^2 with a minimum value of 17.91 mag/arcsec^2 and a maximum value of 18.30 mag/arcsec^2. Meanwhile, the lowest average night sky brightness value was found at Lippo Plaza Batu (S4), which was 11.81 mag/arcsec^2, with a minimum value of 11.37 mag/arcsec^2 and a maximum value of 12.11 mag/arcsec^2. The measurement data shows that each observation location has varying night sky brightness.

The measurement data results show that locations S1 and S2 tend to have higher average MPSAS values compared to other locations. This is because locations S1 and S2 are located in residential or rural areas. Lower average MPSAS values compared to locations S1 and S2 are shown in locations S3 and S5. Location S3 is a location that is actually still in a residential or rural area but is already moving towards the urban center. In addition, location S3 is also a performing arts tourist attraction, so the quantity of artificial light in the surrounding area is higher compared to locations S1 and S2. On the other hand, location S5 shows a lower average MPSAS value compared to location S3. This is because location S5 is the city center and urban public space, so the quantity of artificial light in the surrounding location is higher compared to location S3. The average MPSAS value is shown in locations S4 and S6. Location S6 is a central government area located very close to the city center. Despite not being located directly in the city center, location S6 has a lower average MPSAS value compared to location S5, which is in the city center. This may be due to the higher quantity of artificial light around location S6 compared to location S5. A similar condition also occurs for location S4, where the average MPSAS value is lower despite being further away from the city center compared to location S6. This could be due to the higher quantity of artificial light around location S4 compared to locations S5 and S6, as S4 is a commercial area. The low average MPSAS score at location S4 could also be due to the high commercial activity and visitor mobility at night. This situation results in more intensive use of artificial light compared to location S6, which is geographically closer to the city center.

At each observation location, the Bortle classification results are within the VII-IX class range. Only one location falls within class VII, while the other five locations fall within classes VIII-IX. Location S1, which falls within class VII, has a suburban/urban transition sky type. Meanwhile, location S2, which falls within classes VIII-IX, has a city sky/inner-city sky type. Although locations S1 and S2 are still considered residential or rural areas, this indicates that both locations have experienced a decline in the quality of the night sky's brightness due to the influence of artificial lighting from the surrounding urban areas. Furthermore, the relatively close proximity of S1 and S2 to urban areas compared to other sub-districts allows for light to spread from urban to rural areas. The use of artificial light at night can spread long distances from its source through atmospheric scattering, thus affecting the night sky conditions in rural and natural areas (L Massetti, 2020). Therefore, although both locations are still classified as residential or rural areas, the measured night sky brightness conditions are more representative of the transition zone between suburban and urban areas and the city or downtown zone. A similar condition occurs at location S3. Location S3, which is classified as class VIII-IX, geographically has the characteristics of a rural-to-urban transition area. However, the measurement results indicate that the type of night sky brightness at this location, when interpreted according to the Bortle classification, is more representative of the city or central city zone.

Locations S4, S5, and S6 are classified as classes VIII-IX. Based on the measurement data, it can be seen that the night sky brightness type at these three locations, when interpreted according to the Bortle classification, represents an urban or central zone. This aligns with the regional characteristics of the three locations. Geographically, these three locations have characteristics of an urban or central city area.

The MPSAS values obtained in this study indicate that the brightness of the night sky decreases as a location gets closer to the city center. The closer a location is to the city center, the lower the MPSAS value. This may be due to the high intensity of artificial light use in urban areas, which can produce artificial skyglow, which is an increase in the luminance of the night sky due to the scattering of artificial light in the atmosphere (Falchi et al., 2016). Artificial light in urban areas can come from streetlights, buildings, and human activity. Skyglow is formed by the interaction of artificial light at night (ALAN) with atmospheric particles that scatter the light (Kocifaj & Barentine, 2021). The pattern of decreasing night sky quality as we move towards the city center obtained from this study is in line with the results of previous studies which showed that the highest skyglow values were found in the city center and decreased gradually towards the city limits and areas outside the city (Jechow et al., 2020). The results of previous research conducted in North Sumatra Province also showed that locations far from large cities and close to the open sea provide excellent sky clarity and night sky quality (Putraga et al., 2023).

3.2 Comparison of measurement results with light pollution map (LPM)

Night sky brightness can also be obtained by viewing the sky brightness data available on the light pollution map. The data contained in the light pollution map can be compared with the measurement data obtained. The comparison of the measurement data and the data on the light pollution map was carried out to identify the level of agreement between the field measurement data and secondary data and to obtain a more comprehensive representation of the night sky brightness. Furthermore, the data comparison was also conducted to determine whether the remote sensing-based data could represent the actual light pollution conditions at the observation location in Batu City. The results of the comparison of the field measurement data and the data on the light pollution map are presented in Table 4.

Table 4. Comparison of night sky brightness data from measurements and light pollution map

Site Code	Measured MPSAS (mag/arcsec^2)	Bortle's Class (Measured)	LPM MPSAS (mag/arcsec^2)	Bortle's Class (LPM)	ΔMPSAS (mag/arcsec^2)
S1	18.10	VII	20.46	IV	2.36
S2	17.63	VIII-IX	20.46	IV	2.83
S3	15.90	VIII-IX	20.32	IV	4.42
S4	11.81	VIII-IX	19.79	V	7.98
S5	15.04	VIII-IX	20.28	V	5.24
S6	12.48	VIII-IX	20.45	IV	7.97

Based on the data in Table 4, it can be seen that the average MPSAS value from the measurements ranges from 11.81 to 18.10 mag/arcsec^2, while the MPSAS value from the light pollution map ranges from 19.79 to 20.46 mag/arcsec^2. This comparison indicates a difference between the measured night sky brightness data and the data from the light pollution map. In general, the data from the light pollution map provides a darker estimate of the night sky conditions compared to the measured data. The absolute difference between the two datasets ranged from 2.36 to 7.98 mag/arcsec^2, with a mean absolute error (MAE) of 5.13 mag/arcsec^2, indicating a substantial systematic overestimation of night sky darkness by the LPM data. Figure 3 further illustrates the spatial distribution of the two datasets across the observation sites. Compared with the relatively uniform LPM estimates, the field measurements exhibit greater spatial variability, with markedly brighter night sky conditions observed at Sites S4 and S6.

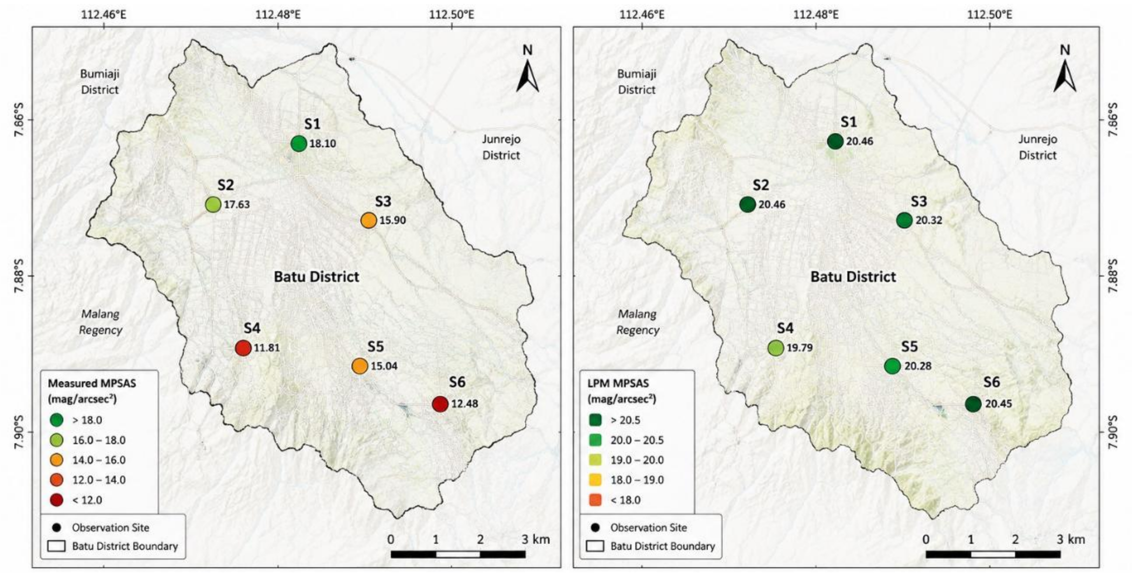

Fig. 3. Spatial comparison of measured and LPM-derived night sky brightness (MPSAS) across the observation sites

These differences are also reflected in the Bortle class classification results shown in Table 4. The measurement data grouped most observation locations in classes VIII-IX, representing urban or central city sky types. On the other hand, the Bortle class classification results for the light pollution map data were in the IV-V range, representing brighter rural/suburban transition and suburban sky types. A comparison of the Bortle class classification results for the two data sets also shows that the data from the light pollution map provided a darker estimate of night sky conditions compared to the data from direct measurements at the observation locations.

These differences in data may be due to several factors. The first factor is thought to be due to the limited spatial resolution of the satellite data used in the light pollution map. Satellite data in the light pollution map represents average conditions over a wider area based on modeling results and satellite observations. Sky brightness modeling is highly complex because the properties of light emissions (spatial and spectral distribution) are generally unknown and the physical state of the atmosphere cannot be determined independently (Kolláth et al., 2021). Data analysis from satellite results has many advantages, but also has several weaknesses due to fluctuations in the measurement results (Cavazzani et al., 2020).

In addition to the limitations associated with satellite-based estimates, field measurements are also subject to several sources of uncertainty. Although the photometer was directed toward the zenith during observations, direct or reflected light from nearby artificial light sources cannot be completely eliminated, particularly in densely illuminated urban environments. In environments illuminated by artificial light, nearby light sources are suspected to play a role in the overall observed sky radiation (Bará et al., 2023). Therefore, the discrepancies between the two datasets are likely attributable to a combination of local measurement conditions and the inherent limitations of satellite-based estimates.

The data discrepancy may also be due to differences in data collection times. Direct measurements at the observation sites were taken on March 17, 2026, while the data contained in the light pollution map are sourced from satellite imagery-based modeling and sky brightness measurements obtained in previous time periods. For example, the VIIRS layer on the light pollution map is constructed using annual aggregation of NASA satellite data, so the values displayed reflect average conditions over a specific time period, not the actual conditions at the time of the direct measurements at the sites.

A Spearman rank correlation analysis yielded $\rho = 0.81$ ($p = 0.050$, $n = 6$), confirming a strong positive relationship in the spatial ranking of sky brightness between both datasets, though this result should be interpreted cautiously given the small sample size. Even though there are differences in the MPSAS scores and Bortle class classification, the two data in Table 4 still show the same pattern trend. Locations with higher urban activity characteristics tend to have lower MPSAS values than locations characterized by residential/rural areas. Therefore, light pollution map can still be used as a tool for initial identification of night sky brightness conditions and direct measurements in the field still need to be carried out to validate and obtain a more accurate picture of night sky brightness conditions.

3.3 Analysis of light pollution and its implications for the potential development of astrotourism

Pollution can be defined as the presence of a substance that has a dangerous and detrimental impact on living things (Shariff et al., 2020). Light pollution is the deviation of natural lighting at night due to the presence of excessive artificial (anthropogenic) light sources (Falchi et al., 2016; Jechow et al., 2020). Light pollution has become a worldwide and cross-disciplinary environmental concern, significantly transforming night-time settings and garnering more focus from various scientific fields (Bará & Falchi, 2023; Mander et al., 2023). In addition, light pollution is also considered to be a serious environmental pressure for animals and plants and can affect human health (Barentine et al., 2024; Falchi et al., 2016; Umar et al., 2025). Light pollution is a waste of energy which is generally accompanied by increased ground surface lighting to a considerable distance from residential areas and hinders research and observation activities about the universe (Green et al., 2022). Therefore, it is important to analyze the presence of light pollution in an area.

The level of light pollution in an area can be determined using the night sky brightness parameter. The night sky brightness value is measured using a photometer and expressed in units of mag/arcsec^2 (MPSAS). A higher MPSAS value indicates darker skies and lower levels of light pollution. Conversely, a lower MPSAS value indicates brighter skies and higher levels of light pollution. Direct measurement data at the observation locations showed that the average MPSAS value at each location was relatively low, ranging from 11.81 to 18.10 mag/arcsec^2. This indicates that light pollution in Batu City, particularly in Batu District, is already quite high. The highest light pollution was at location S4 and the lowest was at location S1. The measurement data also indicates that urban areas or city centers have higher levels of light pollution compared to residential/rural areas. This aligns with previous research showing that skyglow intensity, a form of light pollution, is found in city centers and gradually decreases towards rural areas (Jechow et al., 2020). Previous research in Indonesia also showed that observation locations located in or near urban areas, such as Bandung and Pasuruan, had higher levels of light pollution compared to locations further from the city center (Admiranto et al., 2019). The results of a similar study conducted in Medan showed that high intensity light pollution occurred in the city center where activity and population in the area were also higher (Putraga et al., 2023).

As a city known for its tourism and natural beauty, Batu City actually has the potential to develop astrotourism as a tourist attraction. Astrotourism refers to a type of travel where individuals have the opportunity to view, investigate, and appreciate the splendor of the night sky along with various celestial events, usually by going to locations with minimal artificial light influence (Pásková et al., 2021). Astrotourism may also be classified as a type of tourism centered around nature, wherein travelers are inspired to journey to natural locations with minimal light pollution in order to encounter distinctive surroundings and celestial phenomena that cannot be found in their hometowns (C-Sánchez et al., 2019; Escario-Sierra et al., 2022).

Developing astrotourism requires specific requirements or conditions. A good night sky is essential for observing astronomical phenomena, which are the primary attraction of astrotourism. The quality of the night sky is a key factor in determining the success of astrotourism activities. Astrotourism utilizes the night sky, free from light pollution, as its primary resource (Escario-Sierra et al., 2022). This is because various activities such as observing night sky objects, astrophotography, stargazing, and astronomy education are highly dependent on dark skies and minimal artificial light interference. Therefore, assessing light pollution is essential not only for evaluating the feasibility of astrotourism but also for identifying locations where dark-sky preservation could support sustainable tourism development.

Light pollution in Batu City, particularly in Batu District, indicates that the night sky brightness at the observation locations is generally poor. Only location S1 exhibited the best sky conditions, with an average MPSAS value of 18.10 mag/arcsec^2. However, the overall average MPSAS value was significantly lower than those typically found in dark-sky areas. This value is also still below the range of night sky brightness generally considered ideal for astrotourism activities. The International Dark-Sky Association states that the recommended value for Dark Sky Park areas is ≥21.2 mag/arcsec^2 (International Dark-Sky Association, 2018). These results indicate that observations of night sky objects will be limited at most study sites due to high levels of light pollution. This aligns with research suggesting that increased skyglow due to human activity has become a major threat to night sky quality, even at locations relatively far from light sources (Green et al., 2022).

Although the measured light pollution levels are high, this study's findings do not completely rule out the development of astrotourism in Batu City. This is because differences in average MPSAS values between observation locations indicate that light pollution levels in Batu District are not evenly distributed, meaning that some locations are relatively better suited for astrotourism development than others. Preserving and improving night sky quality at these locations could support tourism diversification by expanding Batu City's tourism portfolio beyond its existing nature and recreation based attractions. Furthermore, preserving dark skies may strengthen destination competitiveness by reinforcing Batu City's distinctive destination identity through the conservation of a unique natural nighttime environment, an important element in destination branding (Rodrigues & Schmidt, 2021). However, the results of this study also demonstrate the need for light pollution control efforts as part of urban development policies. Therefore, identifying locations with better night sky quality and implementing light pollution mitigation strategies should become important considerations for sustainable tourism planning in Batu City.

3.4 Limitations

This study has several limitations that should be acknowledged. The observation sites were confined to a single sub-district, which limits the spatial representativeness of the findings and prevents generalization to the entirety of Batu City. Additionally, the short observation period does not account for potential seasonal variability in night sky brightness, which may fluctuate with changes in atmospheric conditions, precipitation patterns, and human activity across different times of the year. Future studies should therefore consider expanding geographic coverage to include all sub-districts in Batu City and conducting measurements across multiple seasons with a longer duration, so as to provide a more comprehensive and reliable assessment of night sky quality and astrotourism potential.

The limitation of this study also lies in the airglow conditions which have not been controlled explicitly. Airglow is a natural light emission originating from the Earth's atmosphere due to chemical reactions and the de-excitation process of atoms and molecules in the upper atmosphere (Yankovsky, 2021). This phenomenon contributes to the brightness of the natural night sky and can therefore affect the sky brightness values measured using the Sky Quality Meter (SQM). Airglow is present every night with intensity that can vary depending on solar activity, season, time of night, and atmospheric conditions. Airglow also cannot be eliminated so natural night skies are very rare even though measurements are taken during periods of solar activity at very low minimum levels (Grauer & Grauer, 2021). In this study, the relative contribution of airglow to the measurement results is estimated to be smaller than the influence of anthropogenic light pollution. This is because all observation locations exhibited relatively high levels of artificial light pollution. Nevertheless, future research is expected to consider airglow conditions when conducting measurements to reduce potential uncertainty in the results. Furthermore, measurements can be repeated under comparable atmospheric conditions. This way, the contribution of airglow to the measured night sky brightness can be more accurately identified and separated from the influence of artificial light pollution.

This study also have technical limitation at two locations so that the amount of data recorded at the two observation locations is less than the specified observation duration. Therefore, it is hoped that future research will be able to implement instrument verification before and after measurements, real-time monitoring of data recording, as well as re-measurements at locations experiencing recording anomalies.

The findings regarding the potential of astrotourism in Batu City in this study should be viewed as preliminary. Considering several existing limitations, generalizations regarding the potential for astrotourism development in Batu City need to be strengthened with further research. Therefore, future research is expected to consider the aforementioned limitations. This will provide a stronger basis for assessing astrotourism development in Batu City.

4. Conclusions

Based on the research results, it can be concluded that the quality of the night sky brightness in Batu District decreases as a location gets closer to the city center. The average MPSAS value in locations with residential/rural characteristics is higher than those in the city or city center. In general, based on the Bortle classification, the research results indicate that most observation locations are classified as city to city center sky types. This indicates a significant influence of light pollution on night sky conditions in Batu District. Furthermore, the results of the data comparison with data from the light pollution map show differences in night sky brightness values and Bortle classes, where the light pollution map data provides an estimate of the night sky conditions that are darker than the results of field measurements. Nevertheless, both data sources show the same pattern of decreasing night sky quality in areas with higher levels of activity and artificial lighting sources.

High levels of light pollution indicate that most of the observation sites studied are not yet ideal for supporting astrotourism development. However, the results of this study cannot be used to describe conditions throughout Batu City because the research was limited to one sub-district. The variation in the average MPSAS value between observation locations shows that there is still an opportunity to identify locations in other sub-districts with better night sky quality. Therefore, based on this preliminary single-night measurement, it is premature to draw firm conclusions regarding astrotourism potential. Future studies covering all sub-districts and repeated observations under different observational conditions are needed to provide a more comprehensive assessment of night sky quality and astrotourism potential in Batu City. Nevertheless, policymakers and urban planners are encouraged to consider regulating the intensity, direction, and spectral composition of artificial lighting in areas with relatively better sky quality, while tourism stakeholders may explore the feasibility of dark-sky tourism in the less light-polluted peripheral areas of Batu City pending more comprehensive assessments.

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Author Contribution

DF contributed to the conceptualization of the study, formal analysis, data curation, visualization, project administration, and preparation of the original manuscript draft. DF, YKS, IR, and NF contributed to the methodology development, data collection, and investigation process. CPA contributed to the development of the photometer instrument used in this study and provided technical resources related to astronomical observations. Validation of the research findings was carried out by all authors. YKS, IR, NF, and WL contributed to reviewing and editing the manuscript. WL provided supervision, research guidance, and resources throughout the study. All authors have read and approved the final version of the manuscript.

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Not available. This study did not involve human participants, animals, personal data, public helath interventions, or any activities requiring ethical review board approval.

Informed Consent Statement

Not available. This study did not involve human participants or the collection of personal data; therefore, informed consent was not required.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used several tools such as Google Translate and ChatGPT. Google Translate were used by the author to assist in translating the text from Indonesian to English. The translation results from Google Translate were then adjusted by the author according to needs. Furthermore, ChatGPT was used by the author for discussions and brainstorming to improve the quality of the manuscript according to academic requirements. ChatGPT was also used by the author to help create a map of the research location. The results of using ChatGPT were not directly used by the author but were reviewed thoroughly and in depth as needed. The author is fully responsible for the content of the publication.

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