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Temporal-Spatial Impact of the COVID-19 Pandemic on Land Surface Temperatures in Kuta, Bali: An Analysis Using Landsat 8 Satellite Imagery

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Abstract: In 2020, the world witnessed an unprecedented event: the outbreak of the COVID-19 pandemic, leading to significantly curtailed human activities. This study sought to elucidate the potential spatial ramifications of this on land surface temperatures (LSTs) in the renowned tourist locale of Kuta, Bali, Indonesia. Landsat 8 satellite imagery from 2019-2021, complemented by spatial data from local agencies, was employed for this analysis. LST processing was achieved through the calculation of Spectral Radiance/Top of Atmosphere, Brightness Temperature, and the conversion of Brightness Temperature to actual LST. In 2019, observed LSTs in Kuta District varied from 20.1℃ to over 32℃, with the predominant temperature range being 28.1℃ - 31.99℃, covering an expansive 1487.03 ha or 70.26% of the entire area. By 2020, a notable decline was discerned with temperatures peaking at 27.99 ℃ and the most prevalent temperature range being 24.1℃ - 27.99℃, encompassing an area of 1105.46 ha (52.23%). Contrarily, 2021 experienced an upswing, with the apex temperature touching 31.99℃, and the dominant temperature bracket being 28.1℃ - 31.99℃, spanning 974.90 ha (46.06%). A discernable correlation was identified between tourism activities and LST fluctuations, with temperature reductions conspicuous in zones endowed with tourism amenities.

Keywords: Land surface temperature; Tourism; Remote sensing; Geographic information system

1 Introduction

Urbanization, if unchecked by environmental considerations, may inadvertently usher in a plethora of challenges, chief among them being amplified urban temperatures. Such elevations are often observed in urban sprawls characterized by dense infrastructural developments, prolific industrial sites, and prevalent use of air conditioning [1]. The disparities in air temperatures are chiefly attributed to variations in surface temperatures [2–4].

LST, defined as the temperature at the exterior of an entity [5, 6], varies based on the nature of the entity. For exposed terrains, LST indicates the temperature of the topmost soil stratum, while in vegetative landscapes, such as forests, it pertains to the canopy's surface temperature, and in aquatic environs, it mirrors the water surface temperature [7]. Several anthropogenic activities — transportation, industrialization, erection of impermeable structures, waste production, and domestic energy consumption — are identified as principal influencers of LST [8]. A significant uptick in impervious formations can instigate land cover alterations, predominantly transforming vegetative plots into non-vegetative expanses, thus catalyzing a surge in soil surface temperature [9]. Excluding the omnipresent specter of global warming, escalations in LST are often induced by communal activities engendering gas emissions, complemented by burgeoning vehicular traffic and vehicle proliferation [10].

The advent of the COVID-19 pandemic in 2020 instituted unparalleled restrictions on societal functions. Governments globally, in a bid to mitigate viral transmission, endorsed several constraining measures, inclusive of remote working mandates, academic instruction from homes, regulated commercial operations, and overarching mobility curtailments. In tandem with global measures, the Provincial Government of Bali enforced the Corona Virus Disease 2019 Emergency Restrictions on Community Activities (PPKM). Under this edict, non-essential sectors were shuttered and a comprehensive work-from-home directive was promulgated, culminating in markedly diminished human mobility, curtailed transportation utilization, and stymied public infrastructure developments.

Given these profound alterations in societal operations, the post-pandemic evaluation of LST variations becomes pivotal. Touristic hubs, perennially teeming with activity, witnessed a marked desolation due to imposed travel interdictions, congregation prohibitions, and work-from-home edicts. Kuta District, a precinct in Badung Regency, Bali, Indonesia, with an expanse of 17.52 km² and situated south of the equator, epitomizes such impacted regions [11]. Characterized by temperatures fluctuating between 24°C and 31°C annually and seldom deviating beyond 22°C or 33°C, Kuta District has been acclaimed as an international touristic nexus [12, 13]. Enriched with myriad star hotels, eateries, villas, and shopping centers, its vibrant tourism-driven economy grinded to an unprecedented halt due to the pandemic's onslaught. Utilizing advanced technologies like remote sensing and Geographic Information Systems (GIS), this investigation endeavors to be the pioneer in appraising LST alterations vis-à-vis the COVID-19 pandemic in Balinese tourist sectors.

2 Methodology

2.1 Study Site Description

Kuta District, nestled within Badung Regency of Bali, Indonesia, encompasses an area of 17.52 km². Situated a mere 11.42 km away from Denpasar City, the provincial capital of Bali, this district comprises five distinct villages or sub-districts: Kedonganan, Tuban, Kuta, Legian, and Seminyak. Geographically, it is delineated by North Kuta District to its north, South Kuta District to its south, the Bali Strait on its eastern periphery, and the expansive Java Sea to its west [11].

Renowned internationally for its pristine beaches, with Kuta Beach being the most celebrated [14–16], Kuta District also boasts the distinction of housing the principal international airport of Bali, notably situated within Tuban Village. The contiguous shoreline encompassing all villages has further augmented Kuta's reputation for its unparalleled coastal beauty. Its propinquity to the capital and the strategic placement of an international transportation hub have invariably heightened tourist influx, further fortifying its status as a prime touristic epicenter. The geographical extent of the study site is depicted in Figure 1.

Figure 1. Geographic representation of the study site

2.2 Methodological Framework

The methodology hinged upon dual axes: spatial and temporal, spanning the pre-pandemic and pandemic phases of COVID-19. Both spatial and temporal dimensions hold significant value in spatial planning, offering distinct yet complementary insights into patterns and temporal shifts [17–19]. A spatial assessment was executed to discern the geographical attributes of the entire Kuta district, particularly focusing on temperature variations and land utilization. Temporally, a data series encompassing the years 2019 through 2021 — representing both pre and post-pandemic timelines — was meticulously analyzed. The research unfolded through distinct stages, delineated as: (1) Preliminary Study Phase, (2) Data Pre-processing, (3) Data Processing, (4) LST Value Distribution Analysis, and (5) Validation.

2.2.1 Preliminary study phase

This phase was inaugurated with the accrual of secondary data sources, predominantly Landsat 8 satellite imageries spanning 2019-2021. The captured images elucidate conditions before and amidst the pandemic. The distinguishing feature of Landsat 8 lies in its capacity to archive images across varied spatial resolutions, fortified with 11 channels (bands). This satellite is outfitted with dual sensor instruments: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI serves as the primary sensor, specialized in assimilating data pertaining to the Earth's surface with precise spatial and spectral resolution specifications. These images were sourced from the United States Geological Survey's portal [20, 21]. The thermal infrared channel embedded within Landsat imagery facilitates LST analyses. The overarching advantage of Landsat imagery encompasses its free access, coupled with a comprehensive data series enveloping all Indonesian territories. Ancillary spatial datasets, inclusive of administrative demarcations, road architectures, and pinpointed locations, were procured from regional agencies.

2.2.2 Data pre-processing

Embarking upon this stage entailed three pivotal steps: atmospheric rectification, image geometric refinement, and strategic image cropping. Systematic geometric rectifications were imperative to rectify inherent distortions resulting from Earth's rotation, sensor viewing angles, vehicular speed, trim distortion, and sprinkler line inclinations [22]. The objective behind atmospheric corrections was two-fold: to negate atmospheric interferences on sensor-recorded remote sensing data [23, 24], and to counteract spectral reflections induced by atmospheric perturbations during the image capture process [25]. Cropping was administered by delineating a set of coordinates within the image domain, with two primary coordinates defining the span of the cropped image.

2.2.3 Data processing

The LST was analyzed utilizing Landsat 8 satellite imagery spanning the years 2019 to 2021. The processing of the LST underwent several intricate stages, as detailed in the study [26]:

(1) Spectral Radiance/ Top of Atmosphere Calculation

(2) Transition from Top of Atmosphere to Brightness Temperature

(3) Conversion from Brightness Temperature to LST

Initially, the Radian Top of Atmosphere (ToA) value was derived through radiometric correction applied to the Landsat-8 imagery. This radiometric correction was necessitated due to discrepancies originating from the optical system, disturbances from electromagnetic radiation within the atmosphere, and deviations resulting from the sun's elevation angle. Subsequently, the Brightness Temperature, an electromagnetic wave radiation identifiable by the Landsat 8 thermal sensor, was computed to facilitate the estimation of LST [27–29].

1) The Spectral Radiance/Top of Atmosphere is derived utilizing the relation in Eq. (1):

$$L\lambda' = MLXQ\text{cal} + AL \tag{1}$$

$L\lambda' =$ Spectral Radians / Top of Atmosphere

$ML =$ Multiplication Scale Factor

$AL =$ Adding Scale Factor

Qcal = Standard Product Pixel Values or Digital Number (DN).

2) The conversion from Spectral Radiance to the Brightness Temperature (BT) is articulated in Eq. (2):

$$BT = \frac{K2}{\lceil (\frac{K1}{L\lambda}) + 1 \rceil} - 273.15 \tag{2}$$

$K1$: Spectral radian calibration constant

$K2$: Absolute temperature calibration constant (K)

$L\lambda'$: Spectral Radians

3) Upon procuring the Brightness Temperature values, the subsequent phase encompassed the transformation of Brightness Temperature to the land surface temperature, as represented in Eq. (3):

$$LST = \frac{BT}{\{1 + (\frac{\lambda * BT}{c2}) * \ln(e)\}} \tag{3}$$

BT = Brightness temperature
Λ = The central wavelength
$C2$ = 14388 µmK
Furthermore, emissivity *(e)* was computed through Eq. (4):

$$\text{e: } 0.004 * \text{PV} + 0.986 \tag{4}$$

The Proportion of vegetation Pv was derived using Eq. (5), while the Normalized Difference Vegetation Index NDVI was determined via Eq. (6), with:

$$PV = \left(\frac{NDVI - NDVI\min}{NDVI\max - NDVI\min} \right) \tag{5}$$

$$NDVI = \frac{\rho\text{NIR} - \rho\text{RED}}{\rho\text{NIR} + \rho\text{RED}} \tag{6}$$

$NDVI$ = Normalized Difference Vegetation Index
NIR = Near Infrared channel
Red = Red channel

2.2.4 Distribution analysis of LST

During this phase, the LST values were computed using ArcGIS. Subsequently, a transformation from Raster to Vector was conducted to discern both spatial and temporal distributions.

2.2.5 Validation

To ascertain the potential shifts in LST attributed to the Covid-19 pandemic within tourist locales, a comparative study was undertaken, juxtaposing variations in LST with the presence of tourism infrastructure, encompassing hotels, restaurants, and vehicular access routes. Data pertaining to the locations of hotels and restaurants were procured from the Badung Regency Tourism Office. Concurrently, road network information was sourced from the Badung Regency Planning Office. A schematic representation of the research methodology can be observed in Figure 2.

3 Results and Discussions

In 2019, land surface temperatures in the Kuta District were observed to span from 20.1°C to an excess of 32°C. Predominantly, a substantial 70.26% of Kuta District, equivalent to 1487.03 ha, was enveloped in the temperature bracket of 28.1°C - 31.99°C. The subsequent range, from 24.1°C – 27.99°C, encompassed 494.05 ha, accounting for 23.34% of the district's total expanse. A marked decrement in land surface temperature was noted in 2020, wherein the apex value recorded was 27.99 °C. The most prevalent temperature ranges were demarcated between 20.1°C to 23.99°C and 24.1°C to 27.99°C, enveloping areas of 960.32 ha (45.37%) and 1105.46 ha (52.23%), respectively. Contrarily, 2021 witnessed an augmentation in temperatures, with the zenith reaching 31.99°C. The most expansive temperature brackets were from 24.1°C to 27.99°C and from 28.1°C -31.99°C, spanning areas of 1128.61 ha (53.32 %) and 974.90 ha (46.06 %), respectively. Comprehensive visual representations of these temperature fluctuations in the Kuta District are delineated in Figure 3, Table 1, and Figure 4.

Preceding the advent of the Covid-19 pandemic, land surface temperatures in 2019 predominantly oscillated between 28.1°C and 31.99°C. This starkly contrasted the ensuing years, 2020 and 2021, wherein a discernibly cooler temperature range of 24.1°C – 27.99°C was more pervasive. Spatial analysis revealed that the precincts of Ngurah Rai International Airport registered the pinnacle temperatures in 2019. Such elevated temperatures were attributed to the sun's radiant heat absorption by the expansive asphalt runway. Furthermore, it was posited that intensive flight operations anterior to the Covid-19 pandemic exacerbated the thermal elevation within the airport's vicinity. Conversely, the cessation of airport operations in 2020, triggered by the pandemic's outbreak, was identified as the causative factor behind the reduced temperatures observed around the airport during that period.

The environmental ramifications of the COVID-19 pandemic have been manifested in various facets, notably in alterations to the climate. Diminished human endeavors, encompassing urbanization, transportation, industry, and settlement, have been linked to temperature declines [30, 31]. Investigations into the LST prior to and amid the

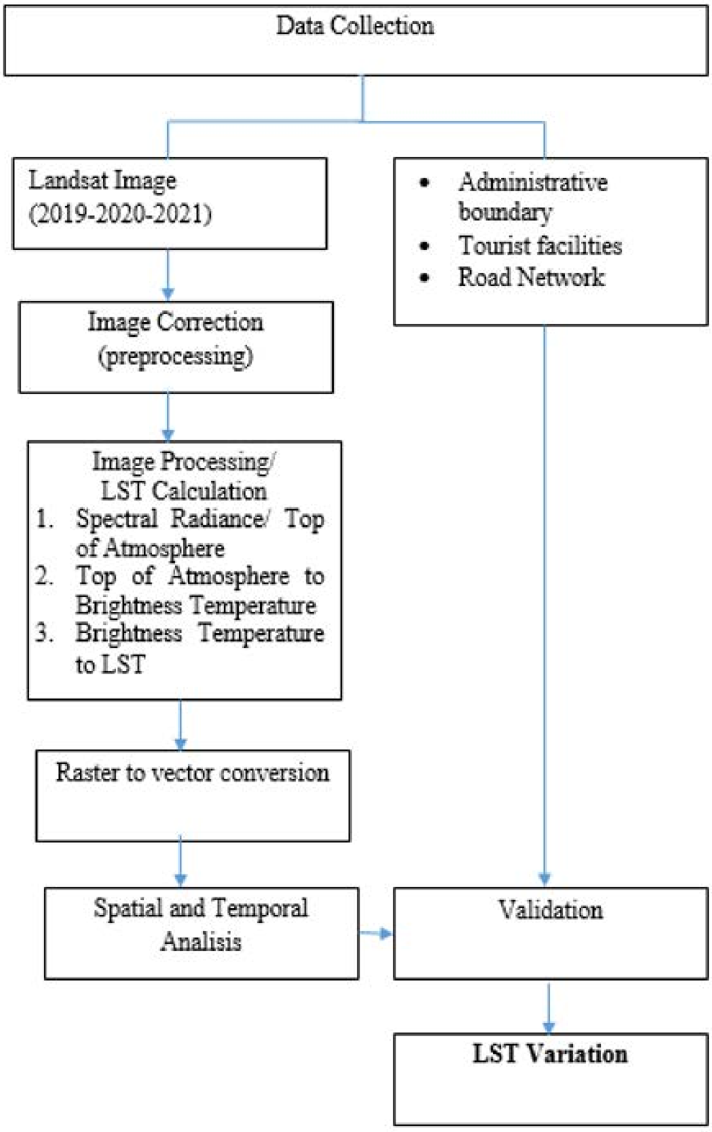

Figure 2. Schematic representation of research procedure

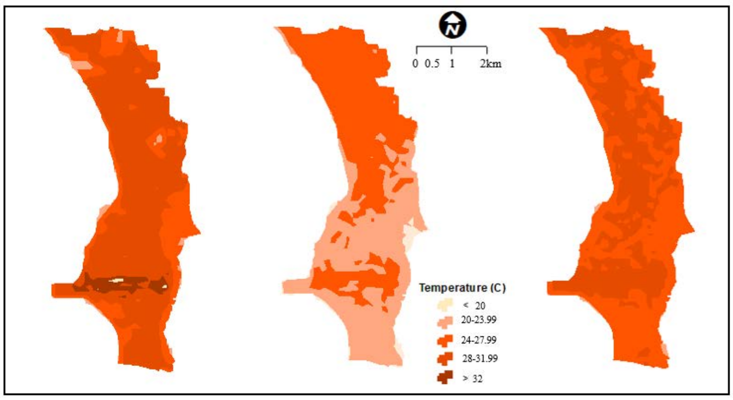

Figure 3. Temporal variations in LST: 2019 (left), 2020 (center), and 2021 (right)

Covid-19 pandemic in regions such as Wuhan City, China [32], Istanbul, Turkey [33], and India [34]have indicated that, during the enforcement of lockdown policies, the average LST was observed to be lower than the periods preceding or following the lockdown.

Table 1. Chronological LST alterations in Kuta District

	2019		2020		2021	
Temp. (°C)	Area (Ha)	%	Area (Ha)	%	Area (Ha)	%
< 20	0	0	50.79	2.40	0	0
$20.1 - 23.99$	48.68	2.30	960.32	45.37	12.77	0.60
$24.1 - 27.99$	494.05	23.34	1105.46	52.23	1128.61	53.32
$28.1 - 31.99$	1487.03	70.26	0.00	0	974.90	46.06
> 32	82.66	3.91	0.00	0	0	0
No Data	4.14	0.19	0.00	0	0.28	0.01
TOTAL	2116.56	100	2116.56	100	2116.56	100

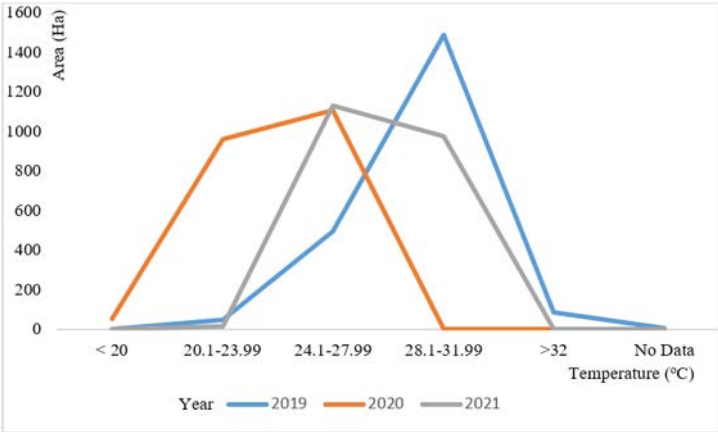

Figure 4. Depictions of LST alterations in Kuta District

Kuta District, renowned globally as a paramount tourist hub in Indonesia, derives its allure not only from its natural grandeur but also its rich cultural heritage. Tourism has been identified as a principal contributor, accounting for 51.6% of the Bali Provincial Original Revenue [11]. As Kuta's prominence burgeoned, so too did its developmental pace. Commensurate with the rise in tourist influx, requisite infrastructures such as transportation avenues, hotels, restaurants, and entertainment facilities witnessed a surge. Such expansions in tourism activity are correlated with temperature increments. It was discerned that in Kuta's tourist-centric areas, the decline in temperature was not solely due to the suspension of flight operations but also the reduced operational cadence of tourism facilities. Data procured from the Badung Regency Tourism Office reveals that 1,172 hotels were operational within the Kuta precinct. Spatial distribution analyses in 2019 illuminated that zones hosting hotels registered higher temperatures than their adjoining areas. Post the outbreak of the Covid-19 pandemic in 2020, a decline in land surface temperatures in hotel-vicinal areas was noted.

Similarly, transportation's influence on the Kuta area's temperature profile was evident. Zones intersected by main roads in 2019 exhibited elevated temperatures compared to non-intersected areas. In 2020, although a decline in LST in the primary roadway zones was observed, these temperatures remained elevated relative to adjacent regions. This can be attributed to the sunlight absorption capabilities of asphalt, leading to augmented surface temperatures. The nexus between tourism and transportation facilities and the LST is delineated in Figure 5.

Field assessments revealed marked LST reductions at locales housing prominent tourism facilities, including hotels, aquatic recreational infrastructures, airports, and beaches. The pandemic-induced downturn in tourism during 2020 culminated in plummeted hotel occupancy rates and curtailed tourist activities in Kuta District. Mangrove forest areas, however, exhibited contrasting temperature profiles, registering lower values. The intrinsic capacity of mangrove forests to modulate the surge in LST is significant. Mangroves facilitate CO2 sequestration, absorbing atmospheric carbon and sequestering it within compartments such as plant stems, litter, and soil organic matter. Photosynthesis enables the conversion of atmospheric CO2 into organic carbon, stored as biomass. This mechanism is instrumental in curtailing the escalation of greenhouse gases, principal contributors to temperature anomalies, global warming, and climatic shifts [35–37]. Table 2 provides a detailed outline of the sampled LST locales within Kuta District, while Figure 6 delineates the distribution of tourist facilities where LST reductions were observed.

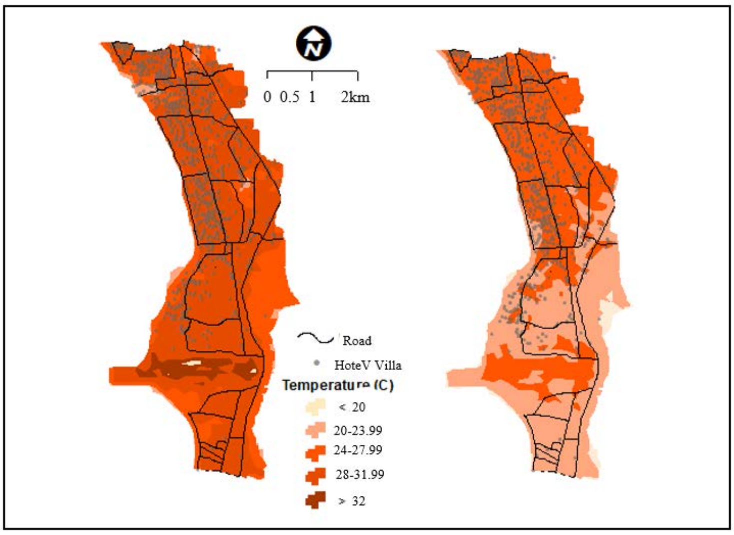

Figure 5. Correlation between tourism and transportation infrastructures and LST. Left: Pre-pandemic (2019). Right: Amid pandemic (2020)

Table 2. Sampling locales detailing LST within Kuta District

Latitude	Longitude	Location	LST
-8.74	115.18	Mangrove forest	Decreased
-8.74	115.163	Ngurah Rai International Airport	Decreased
-8.76	115.17	Jimbaran Bay Beach Resort	Decreased
-8.76	115.169	Kedonganan beach	Decreased
-8.696	115.168	The Haven Bali Seminyak Hotel/ Resort	Decreased
-8.699	115.164	The Jayakarta Bali Beach Resort	Decreased
-8.724	115.186	Mangrove forest	Decreased
-8.728	115.169	Waterbom Bali	Decreased

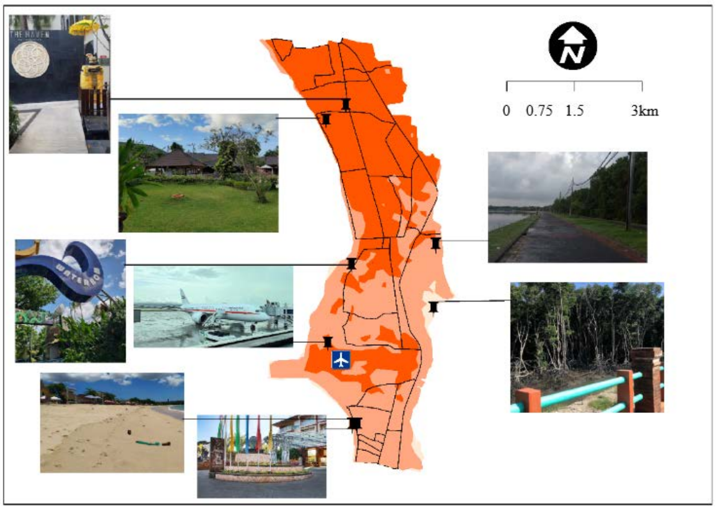

Figure 6. Distribution pattern of tourist facilities corresponding to declining LST in Kuta District

4 Conclusions

Land surface temperatures in the Kuta District were analyzed over a three-year period. In 2019, temperatures were observed to range from 20.1°C to > 32°C, with the most extensive area (1487.03 ha or 70.26% of the total district) exhibiting temperatures between 28.1°C to 31.99°C. By contrast, 2020 witnessed a decrease in land surface temperatures with the highest recorded temperature being 27.99°C. During this year, the largest regions displayed temperatures between 20.1°C – 23.99°C and 24.1°C -27.99°C, encompassing 960.32 ha (45.37%) and 1105.46 ha

(52.23%) of the district, respectively. However, 2021 marked an uptrend, with temperatures reaching up to 31.99°C. The dominant temperature ranges for this year were from 24.1°C – 27.99°C to 28.1°C -31.99°C, which covered areas of 1128.61 ha (53.32%) and 974.90 ha (46.06%), respectively.

It was observed that the presence of tourism activities, particularly in zones with infrastructure like hotels and primary roads, had discernible effects on the land surface temperatures. A reduction in temperature was noted in these areas, which can be attributed to the influence of tourism activities.

For more precise results, the selection of satellite imagery with superior spatial resolution is recommended. An extended observational period is also suggested to account for temporal variation. Further investigations are encouraged to analyze the correlation between land surface temperatures and other environmental parameters, such as alterations in land cover and climatic shifts. The aftermath of the pandemic on regional temperatures also offers a compelling avenue for research, allowing for potential comparisons with other prominent tourist destinations.

Tourism, undeniably, fosters economic growth through job creation and revenue generation. Nonetheless, concomitant environmental pressures have been observed to escalate, in tandem with rising tourist numbers and the burgeoning development of tourism-related infrastructure. These pressures manifest as heightened pollution, sanitation challenges, and fluctuations in climate and temperature. Sustainable tourism not only augments the environmental value but also bolsters its longevity. The harmonization of tourism with environmental stewardship emerges as the pivotal solution to the dual challenges of tourism development and environmental conservation.

Contributions

P.P.K.W analyzed and visualized; N.W.S.S considered the research materials, arranged the field surveys. Meanwhile discussions, reviews and editing conducted together in this study.

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Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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