

Article

Spatial and Temporal Influence of the Kebena River Corridor on Vegetation, Land Surface Temperature, and Built-Up Intensity in Addis Ababa, Ethiopia (2015–2026)

Zhi Li ^{1,*} and Tsegay Haftu Gebremeskel ²¹ College of City Construction, Jiangxi Normal University, Nanchang 330022, China² Urban and Regional Planning, Jiangxi Normal University, Nanchang 330022, China; tsegusha2024@gmail.com

* Correspondence: gmorning1985@163.com

Abstract

Urban river corridors play an important role in reducing urban heat and supporting vegetation, yet their environmental influence is still poorly understood in rapidly growing African cities. This study examined the spatial and temporal relationship between vegetation cover (NDVI), land surface temperature (LST), and built-up intensity (NDBI) along the Kebena River corridor in Addis Ababa, Ethiopia, using Landsat 8 and 9 imagery from 2015, 2018, 2022, and 2026. A buffer-based approach (0–250 m, 250–500 m, and 500–1000 m) was applied to evaluate how these indicators change with distance from the river. The results reveal a clear environmental gradient. The 0–250 m zone consistently showed higher vegetation cover, lower surface temperature, and lower built-up intensity compared with the outer zones. Pearson correlation analysis indicated a significant negative relationship between NDVI and LST ($r = -0.49$ to -0.64) and a strong negative relationship between NDVI and NDBI ($r = -0.83$ to -0.90), while NDBI and LST were positively correlated ($r = 0.51$ to 0.67). Regression analysis further showed that a 0.1 increase in NDVI reduced LST by approximately 2.7–3.9 °C. The river corridor continued to provide measurable cooling benefits, notwithstanding a slight reduction in vegetation cover over the study period. The lower built-up intensity near the river in 2026 is consistent with the timing and recorded activities of the recent Kebena River rehabilitation programme. These results indicate that conservation and restoration of urban river corridors can improve ecological resilience, mitigate the effects of urban heat and support the sustainability of green infrastructure in rapidly urbanising cities. This study offers evidence to guide conservation planning and long-term management of urban riparian ecosystems in Addis Ababa and other cities facing similar environmental pressures.

Academic Editor: Svein
Øivind Solberg

Received: 28 May 2026

Revised: 12 July 2026

Accepted: 20 July 2026

Published: 28 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.**Keywords:** remote sensing; land surface temperature; NDVI; NDBI; urban heat island; urban conservation; river corridor; Addis Ababa

1. Introduction

1.1. Background of the Study

Urbanisation has become one of the most important drivers of environmental change in the twenty-first century, especially in fast-developing cities where population growth and infrastructure expansion often outpace environmental planning [1]. Natural landscapes have been transformed into impervious surfaces that have changed ecosystem processes, reduced vegetation cover, fragmented habitats and increased urban heat islands. These

changes not only threaten biodiversity and ecological integrity but also diminish cities' ability to adapt to climate change and other environmental stresses. The most evident consequence of this process is the substitution of vegetated and permeable surfaces by impervious constructed areas, causing changes in biological conditions and increased surface temperatures [2]. Thus, the conservation and restoration of urban ecosystems are important priorities for sustainable and climate-resilient urban development.

Urban vegetation is a fundamental component of healthy and resilient cities because it provides a wide range of ecosystem services that benefit both people and nature. Urban vegetation moderates heat through shading and evapotranspiration [3]. But cities grow at the expense of vegetation, often reducing or fragmenting it and thus its ability to reduce environmental stress. Built surfaces, mostly composed of materials such as asphalt, concrete and metal, tend to absorb and retain heat, increasing land surface temperatures and contributing to the formation of urban heat islands.

Remote sensing indices such as the Normalised Difference Vegetation Index (NDVI), Land Surface Temperature (LST) and Normalised Difference Built-up Index (NDBI) have been widely used to understand these processes. NDVI is used to quantify vegetation density and health, LST is used to describe the thermal properties of the land surface, and NDBI is used as a measure of built-up intensity [4]. The indices provide a complete framework to analyse the interaction between ecological and urban processes. These indicators are increasingly used in conservation science to monitor vegetation condition, habitat quality, urban expansion, and the effectiveness of ecological restoration programmes over time.

Urban river corridors are among the most valuable conservation landscapes within cities because they preserve riparian vegetation, maintain habitat connectivity, regulate hydrological processes, and provide multiple ecosystem services that enhance urban resilience. Their elongated form enables them to penetrate deep into densely built-up areas, perhaps providing some local environmental benefits such as cooling and preservation of greenery [5]. Nevertheless, increasing urban expansion, informal settlement, pollution, and land-use conversion continue to degrade many urban river systems, particularly in developing countries. Conserving and restoring these riparian ecosystems has therefore become an important nature-based solution for improving urban sustainability while protecting ecological integrity.

Addis Ababa, the capital of Ethiopia, has seen rapid urban growth in recent decades amid growing environmental challenges [6]. The Kebena River passes through densely populated and expanding areas of the city, providing an opportunity to study the relationship between river corridors and urban environmental processes. It is vital to understand the importance of these corridors for maintaining vegetation and controlling temperature in order to develop sustainable urban design plans. In recent years, the Kebena River Corridor rehabilitation programme has aimed to restore degraded riparian environments through the removal of informal settlements, riverbank rehabilitation, and improved green infrastructure. These interventions provide an opportunity to evaluate whether ecological restoration can improve vegetation conditions, reduce built-up pressure, and strengthen the cooling capacity of urban river corridors. Scientific evidence from such assessments is essential for supporting conservation planning and future restoration initiatives in rapidly urbanising African cities.

In this sense, the knowledge of the interactions in space and time between vegetation, temperature, and built-up intensity can provide important clues on the development of urban settings and on the role of natural elements in this process [7]. While remote sensing has been employed in numerous studies to investigate urban vegetation dynamics, land surface temperature, and urban expansion, comparatively few have investigated their

combined spatial and temporal interactions within an urban river corridor conservation framework. This is especially true in fast-urbanising African cities, where empirical evidence on the environmental benefits of river restoration is still scarce. Moreover, little is known about how these relationships change with increasing distance from restored river corridors or the effects of ecological rehabilitation on surrounding environmental conditions over time. Filling these knowledge gaps is critical for assessing conservation effectiveness and informing evidence-based management of urban riparian ecosystems.

The main aims of this article are outlined as follows:

- (1) To provide one of the first buffer-based, multi-temporal assessments of an urban river corridor in Addis Ababa using integrated NDVI, LST, and NDBI indicators.
- (2) To quantify the distance-decay effect of the Kebena River corridor using non-overlapping buffer zones and pixel-level statistical analysis.
- (3) To link remote-sensing evidence with recent corridor rehabilitation, demonstrating how policy intervention can reduce built-up encroachment even when vegetation recovery remains incomplete.

1.2. Problem Statement

There is growing recognition that urban river corridors can act to moderate local temperatures and support flora, but the exact influence of the Kebena River in its environment has not been carefully evaluated. Addis Ababa is undergoing rapid urbanisation, and this has led to the replacement of large areas of vegetation with buildings and impervious surfaces. This shift has led to increasing surface temperatures and a steady decrease in green space. Hence, planners do not have quantifiable data on the cooling and greening effects of the corridor and their temporal stability. In the absence of such evidence, it is difficult to design targeted actions that retain the ecological benefits of the corridor whilst allowing vital urban expansion.

1.3. Research Questions

- (1) What is the spatial extent of the influence of the Kebena River corridor on vegetation cover, land surface temperature and built-up intensity in Addis Ababa?
- (2) What will be the change in vegetation cover, land surface temperature, and built-up intensity in the Kebena River corridor between 2015 and 2026 under continued urban expansion and river rehabilitation?
- (3) What are the relationships between vegetation, built-up intensity and land surface temperature, and how do these relationships explain the environmental regulation function of the corridor?

1.4. Significance of the Study

The study adds to scientific knowledge and to the practical management of cities. The results provide local planners with measurable evidence of the cooler and greener characteristics of the corridor relative to surrounding areas, and how these benefits have evolved over time. This evidence can inform laws protecting buffer zones, investments in green infrastructure, and heat mitigation approaches in Addis Ababa and other rapidly urbanising cities with similar river systems.

1.5. The Scope of the Study

The analysis only covers the Kebena River corridor within the administrative boundary of Addis Ababa city. The spatial parameters are defined by three buffer distances (0–250 m, 250–500 m and 500–1000 m). The four years (2015, 2018, 2022, and 2026) were selected according to the availability of Landsat in the dry season. Only three remote sensing indices

are used, NDVI for vegetation, LST for surface temperature and NDBI for built-up intensity. Factors such as population density, building heights and soil moisture are not considered. The analysis is based on Landsat Collection 2 Level 2 products and traditional GIS methods.

2. Literature Review

2.1. Urbanisation and Environmental Transformation

Urbanisation is a defining process of contemporary global development, particularly in rapidly growing cities of the Global South [8]. Large-scale land-use transformation, in which built-up infrastructure takes the place of natural and semi-natural landscapes, is commonly associated with the expansion of urban areas [9]. The process alters surface characteristics, disrupts ecological systems and changes the energy balance of urban environments. One of the major effects of urbanisation is an increase in impervious surfaces, which decreases infiltration capacity, restricts vegetation growth and increases surface runoff [10]. Simultaneously, the conversion of vegetated land into built-up materials increases the land heat absorption and retention, which results in high land surface temperature [11]. These changes, taken together, increase environmental pressure, affecting both ecological stability and human welfare.

In fast-growing cities like Addis Ababa, the urban development is often characterised by unplanned growth and poor environmental regulation. Hence, it is particularly important to know the impacts of land-cover changes on key environmental variables and the role of natural features within cities to ameliorate these impacts.

2.2. Urban Climate and Vegetation (NDVI)

Vegetation is one of the major factors that regulate the urban environmental conditions, both through the ecological processes and the microclimatic behaviour [12]. Vegetation can help reduce temperature via evapotranspiration and shading, and support biodiversity and improve air quality [13]. In urban settings, vegetation is often unevenly distributed and subject to fragmentation by development pressures.

NDVI is a widely used and reliable indicator of vegetation density and health in remote sensing studies [14]. It allows the Spatio-temporal observation of vegetation dynamics and has been widely used in urban analysis to evaluate the effects of land-use change on green cover [15]. Higher NDVI values are usually associated with dense vegetation, lower values with sparse or no vegetation.

Previous studies have consistently shown a strong inverse correlation of NDVI with land surface temperature, indicating the cooling effect of vegetated areas. However, the extent to which this relationship varies for particular urban features, such as river corridors, remains an area for further investigation.

2.3. Land Surface Temperature and Urban Thermal Environment

LST is an important parameter in understanding the thermal conditions of urban environments [16]. It is a measure of the thermal response of surface materials to solar radiation and is highly affected by the land-cover composition. Built-up areas with materials like asphalt and concrete have higher LST due to their high heat capacity and low albedo [17]. Vegetated and wet surfaces, on the other hand, usually have lower temperatures due to cooling processes.

The concept of the urban heat island (UHI) is closely related to LST, which refers to the phenomenon that urban areas are substantially warmer than the surrounding rural areas [18]. In urban areas, remote sensing techniques, especially the thermal infrared bands of satellite imagery, have been widely used to map and analyse LST patterns [19].

LST is closely related to both vegetation cover and built-up intensity [20], as studies have shown. However, LST is also influenced by atmospheric conditions, and it is important to take into account both spatial patterns and temporal variability in interpreting results. Understanding the variation in LST with specific urban features, such as river corridors, provides valuable insight into localised thermal dynamics.

2.4. Built-Up Index and Urban Expansion (NDBI)

Urban growth is characterised by the increase in built-up areas and has serious implications for environmental conditions [21]. Monitoring built-up intensity is therefore important for understanding urbanisation processes and their impacts.

The Normalised Difference Built-up Index (NDBI) is frequently employed in remote sensing for the identification and quantification of built-up areas [22]. This method is based on the spectral characteristics of urban surfaces, which enables the discrimination between built-up and non-built-up land cover. Generally, values closer to zero correspond to higher built-up intensity, and more negative values are related to non-urban surfaces [23].

NDBI has been extensively used in studies of urban expansion and land use change, frequently combined with NDVI and LST to examine the relationships between urbanisation, vegetation and temperature [24]. Previous studies have shown that the increase in NDBI is generally associated with the decrease in NDVI and the increase in LST, which reflects the environmental impact of the expansion of built-up areas [25].

It is widely used, but there is still a need for more localised analyses that examine how built-up intensity varies with respect to specific spatial features within cities, such as river corridors.

2.5. Urban River Corridors and Green Infrastructure

Urban river corridors are increasingly recognised as critical components of green–blue infrastructure within cities. These corridors serve multiple functions, including ecological connectivity, water management, and microclimate regulation [26]. Their linear structure allows them to penetrate dense urban areas, offering opportunities for vegetation continuity and localised environmental benefits.

Previous studies have highlighted the importance of river corridors in lowering surface temperature, enhancing air quality, and promoting biodiversity [27]. The vegetation along riverbanks helps to cool the air through evapotranspiration, and the presence of water bodies can affect the local humidity and temperature.

However, the effectiveness of river corridors is frequently limited by the patterns of surrounding land use and development pressure [28]. In many cities that are rapidly urbanising, riverbanks are subject to encroachment, informal settlements, and infrastructure development that can reduce their ecological and thermal functions. It is vital for efficient urban planning to understand how these functions change spatially and temporally.

2.6. Urban Environmental Analysis Using Remote Sensing

Remote sensing has become an essential tool for studying urban environmental processes due to its ability to collect consistent, multi-temporal and spatially extensive data [29]. Satellite images, particularly from the Landsat missions, have been widely employed to monitor temporal variations in vegetation, temperature and built-up areas [22].

The integration of remote sensing data such as NDVI, LST, and NDBI provides a comprehensive assessment of the urban environmental conditions [30]. This ability is further augmented with Geographic Information Systems (GIS), which enable spatial analysis such as buffer-based evaluation and zonal statistics.

The use of remote sensing data for multi-temporal analysis is especially valuable in detecting trends and changes in urban areas. Data from different years can be compared to evaluate the influence of urban growth and environmental change.

2.7. Gap in Research

There are still gaps despite extensive research on urban vegetation, surface temperature, and built-up expansion. First, many studies analyse NDVI, LST, and NDBI separately, not fully investigating their combined relationships in one analytical framework. Second, existing research tends to focus on large urban areas, with little attention paid to how environmental conditions differ relative to specific urban features, such as river corridors.

The effect of river corridors on vegetation, temperature and built-up intensity is not studied in detail and spatially explicitly in the context of Addis Ababa. Furthermore, only a few studies have applied buffer-based methods to quantify how these variables vary with distance from such features. Accordingly, this study applies a multi-temporal, buffer-based framework to quantify environmental gradients around the Kebena River corridor.

3. Methodology

3.1. Study Area

Addis Ababa, the capital of Ethiopia, lies in the central highlands of East Africa, at an altitude of about 2300 to 3000 m (7600 to 10,000 feet) above sea level. The Kebena River rises from the northern slopes of the Entoto Mountains and flows south through the central part of Addis Ababa. It meets the Little Akaki River, which in turn meets the Great Akaki River and flows into the Awash River Basin. The river passes through densely populated urban districts, which are under growing environmental pressure from urban expansion, informal settlements and land-use change. It is an important river corridor for assessing urban ecological conservation and restoration. It has a subtropical highland climate with a wet season from June to September and a dry season from October to May. The average annual rainfall is around 1200 mm, and the temperatures are relatively mild for a tropical city, generally ranging between 10 °C and 24 °C in the cooler months and 15 °C to 28 °C in the warmer months. However, the land surface temperature may be much higher in built-up areas, especially during the dry season when the vegetation is sparse, and the solar radiation is high. According to the Köppen climate classification, Addis Ababa has a subtropical highland climate (Cwb), characterised by mild temperatures throughout the year and distinct wet and dry seasons.

In the past 20 years, Addis Ababa has seen some of the fastest urban growth in Africa. The population has grown from about 2.7 million in 2007 to more than 6 million today, which has led to extensive land use conversion. Residential neighbourhoods, commercial districts and transport infrastructure have replaced agricultural land, woodland and riparian zones. This transition has been most noticeable in the southern and eastern sectors of the city, where formal and informal developments have proliferated. The city is situated on undulating plateaus, cut by river valleys that begin in the Entoto Mountains. The variations in elevation contribute to a significant environmental diversity throughout the city, affecting vegetation, drainage, and local thermal conditions. The Kebena River is one of the major river systems crossing the urban core and is part of the ecological connectivity in the fast-urbanising landscape.

3.2. Data Sources

This study relied primarily on Landsat satellite imagery, chosen for its long archive, consistent spectral resolution, and free availability. We used Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) data for 2015, 2018 and 2022, and Landsat

9 OLI/TIRS data for 2026. All images belong to the Collection 2 Level-2 product suite, which provides atmospherically corrected surface reflectance and surface temperature. The acquisition dates were selected from the dry season (January to March) to minimise cloud contamination and to ensure comparability across years. Specifically, we used scenes acquired on 6 February 2015, 13 January 2018, 24 January 2022 and 11 January 2026, all with cloud cover below 5%. The scene path/row is 168/054, and the entire administrative area of Addis Ababa is covered. For each study year, one representative image was used to ensure uniform seasonal and atmospheric conditions for the four dates of comparison. A combination of multiple images from different dates could increase variability due to rain, phenology and short-term temperature variations. However, more robust annual estimates could be achieved using multiple dry-season observations or seasonal composites and the use of only one scene per year is noted as a limitation of the present analysis.

For validation, we used the MODIS Terra Land Surface Temperature product (MOD11A2, version 6.1), which provides 8-day composites at 1 km resolution. MODIS data were obtained for the same dates as the Landsat scenes (within ± 3 days) for the years 2015, 2018 and 2022. The 2026 MODIS data were not used because persistent cloud cover and poor-quality flags made reliable extraction impossible. Additionally, we used the Shuttle Radar Topography Mission (SRTM) digital elevation model to aid in drainage extraction for river delineation and the administrative boundary of Addis Ababa from the Ethiopian Geospatial Information Institute.

Preprocessing

All Landsat images were downloaded from the USGS Earth Explorer portal as Level-2 products. No additional atmospheric correction was necessary because the Collection 2 Level-2 data already include surface reflectance and surface temperature generated using the Land Surface Reflectance Code (LaSRC) and the Single-Channel Algorithm. We reprojected all rasters to the UTM zone 37N (WGS 84) coordinate system to maintain consistent metric units. The images were then clipped to the Addis Ababa boundary using the Extract by Mask tool in ArcGIS Pro 3.4.0 (Esri Inc., Redlands, CA, USA), resulting in city-wide rasters for NDVI, LST and NDBI for each year.

The Kebena River was extracted from the SRTM digital elevation model using hydrological analysis: we computed flow accumulation and retained cells with accumulation above a threshold, then converted the resulting drainage network to a vector line. The river segment that flows through the urban core was manually verified against high-resolution basemaps.

3.3. Index Calculation

3.3.1. Normalised Difference Vegetation Index (NDVI)

NDVI was calculated from the near-infrared (NIR) and red bands of Landsat 8 and 9. For both sensors, Band 5 corresponds to NIR and Band 4 to Red. The formula is:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

Values range from -1 to $+1$, with higher positive numbers indicating denser, healthier vegetation. The calculation was performed directly on the surface reflectance bands using the Raster Calculator tool in ArcGIS Pro, producing a continuous NDVI raster for each year.

3.3.2. Land Surface Temperature (LST)

Land surface temperature was retrieved from the thermal infrared band (Band 10 for both Landsat 8 and 9). The Level-2 product provides the ST_B10 band as scaled integers

(digital numbers). To convert to degrees Celsius, we applied the standard USGS scaling factor and offset:

$$LST(^{\circ}\text{C}) = DN \times 0.00341802 + 149.0 - 273.15 \quad (2)$$

where DN is the digital number of the ST_B10 band. This conversion was applied using the Raster Calculator, producing a continuous LST raster in degrees Celsius for each year. No additional emissivity correction was needed because the Level-2 product already incorporates a scene-based emissivity derived from the Normalised Difference Vegetation Index (NDVI) thresholds method.

3.3.3. Normalised Difference Built-Up Index (NDBI)

NDBI was computed from the shortwave infrared (SWIR) and NIR bands. For Landsat 8 and 9, Band 6 (SWIR) and Band 5 (NIR) were used. The formula is:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \quad (3)$$

NDBI values typically range from -1 to $+1$, with values closer to zero or positive indicating built-up surfaces and more negative values indicating vegetation or water. As with NDVI, the calculation was performed on the atmospherically corrected surface reflectance bands.

3.3.4. NDBI Change Detection

To visualise the spatial pattern of change in built-up intensity, an NDBI difference raster was calculated by subtracting the 2015 NDBI raster from the 2026 NDBI raster:

$$\Delta NDBI = NDBI_{2026} - NDBI_{2015} \quad (4)$$

Positive $\Delta NDBI$ values indicate an increase in the built-up spectral signal between 2015 and 2026, whereas negative values indicate a reduction in that signal. Values close to zero represent limited or no detectable change. Both input rasters were aligned to the same 30 m grid, projected to WGS 84/UTM Zone 37N, and clipped to the Addis Ababa administrative boundary before subtraction. The resulting raster was classified into five categories: strong decrease, moderate decrease, little or no change, moderate increase, and strong increase. The Kebena River and the three non-overlapping buffer zones were overlaid to compare corridor-level changes with the wider city.

3.4. Buffer Analysis

3.4.1. Buffer Zone Delineation

To capture the distance-dependent influence of the Kebena River, we created three concentric buffer rings around the river line using the Multiple Ring Buffer tool in ArcGIS Pro. The distances were set to 250 m, 500 m and 1000 m, and we used the “outside polygons only” option to produce non-overlapping rings: 0–250 m, 250–500 m and 500–1000 m. The 250 m interval was chosen to cover the immediate riparian zone where previous studies have found the strongest cooling and ecological effects of urban rivers. We introduced the additional 250–500 m and 500–1000 m buffers to test the gradual decrease in these effects and to determine the extent of the influence of the river corridor on vegetation cover, built-up intensity, and land surface temperature. This distance approach provides a systematic framework for quantifying environmental gradients from the river corridor to the surrounding urban landscape. Each buffer polygon was saved as a separate feature

class and used as a mask for extracting raster values. Figure 1 shows these buffer zones together with the river and the city boundary.

Study Area and Geographic Location of the Kebena River Corridor, Addis Ababa, Ethiopia

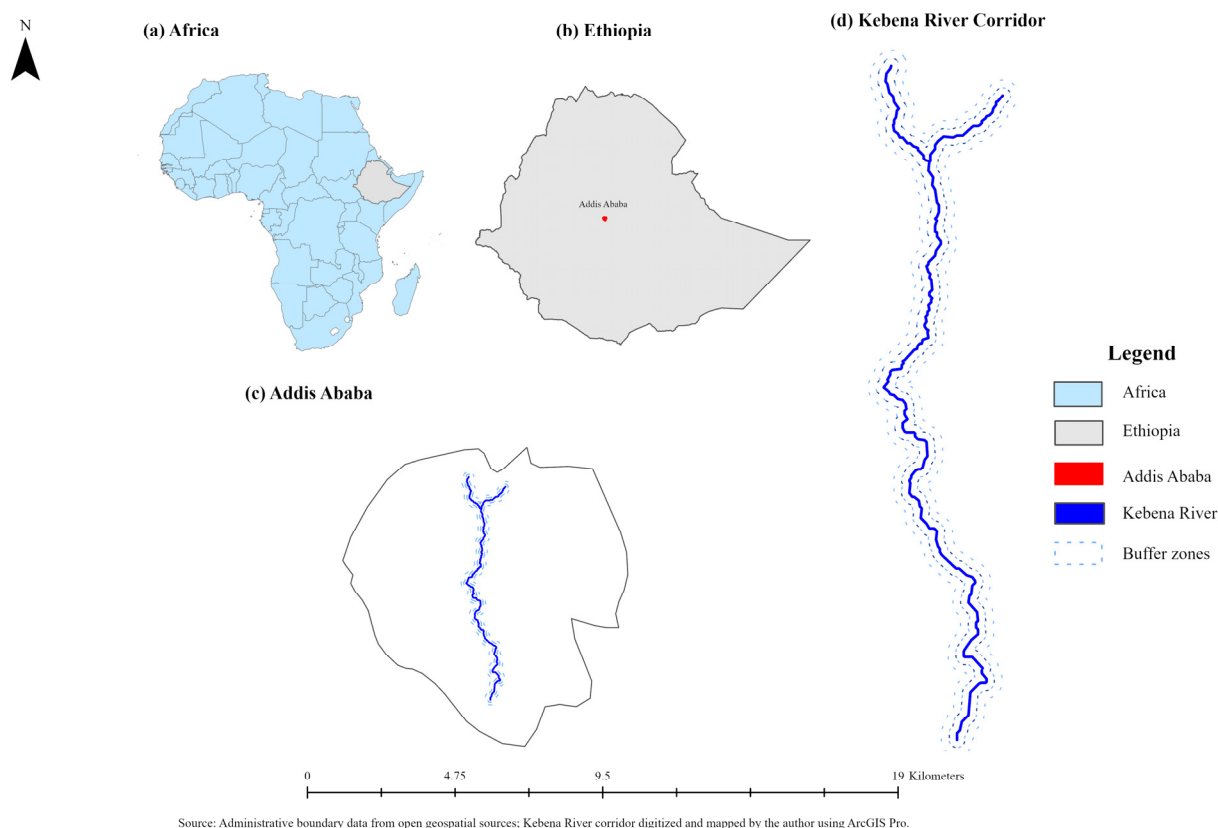


Figure 1. Location of the study area, including Africa, Ethiopia, Addis Ababa, and the Kebena River corridor with the associated buffer zones.

3.4.2. Zonal Statistics

To quantify how NDVI, LST and NDBI vary with distance from the river, we extracted summary statistics for each buffer ring using the Zonal Statistics as Table tool in ArcGIS Pro. For every combination of year (2015, 2018, 2022, 2026) and buffer zone (0–250 m, 250–500 m, 500–1000 m), we calculated the mean, standard deviation, and pixel count of each index. The zone polygons served as the input zones, and the city-wide rasters (clipped to Addis Ababa) were used as the value rasters. This approach ensured that the same underlying data were summarised consistently across all zones. The resulting table (Table 1) provides the core descriptive statistics needed to compare spatial gradients and to support later correlation and regression analyses.

Table 1. Mean NDVI, LST (°C), and NDBI values with standard deviations for each buffer zone (0–250 m, 250–500 m, 500–1000 m) and each year (2015, 2018, 2022, 2026).

Year	Zone (m)	NDVI_mean	NDVI_std	NDBI_mean	NDBI_std	LST_mean	LST_std
2015	0–250	0.128764	0.058862	−0.02277	0.047906	32.91517	3.569203
2015	250–500	0.110999	0.054836	−0.00612	0.043865	34.14923	3.628882
2015	500–1000	0.108554	0.054666	−0.00296	0.043461	34.19443	3.755557
2018	0–250	0.126782	0.056302	−0.02148	0.048017	27.77881	3.13465
2018	250–500	0.110973	0.051248	−0.00566	0.042558	28.87798	3.40695
2018	500–1000	0.10928	0.053628	−0.00384	0.044989	28.833	3.603659

Table 1. Cont.

Year	Zone (m)	NDVI_mean	NDVI_std	NDBI_mean	NDBI_std	LST_mean	LST_std
2022	0–250	0.133491	0.066989	−0.02093	0.052835	31.95582	3.469963
2022	250–500	0.115808	0.060871	−0.00348	0.047749	33.11506	3.587882
2022	500–1000	0.115046	0.063317	−0.00112	0.050696	33.0701	3.865666
2026	0–250	0.120482	0.056346	−0.03241	0.089834	30.04606	2.7738
2026	250–500	0.110302	0.05247	−0.00798	0.085691	30.81366	2.860417
2026	500–1000	0.110145	0.056852	−0.00793	0.092209	30.30427	3.310536

3.5. Statistical Analysis

3.5.1. Correlation and Regression Analysis

We examined the strength and form of relationships among NDVI, LST and NDBI using two complementary approaches: Pearson correlation and linear regression. Pearson correlation analysis was selected because the study aims to quantify linear relationships among continuous environmental variables (NDVI, LST, and NDBI). The analysis was performed using pixel-level observations within each buffer zone rather than aggregated zonal averages, resulting in several thousand paired observations per analysis. This large sample size satisfies the assumptions for Pearson correlation and provides robust estimates of the strength and direction of the relationships among the three environmental indicators.

Pearson correlation. For each year and each buffer zone, we computed the Pearson correlation coefficient (r) between every pair of indices (NDVI–LST, NDBI–LST, NDVI–NDBI). Instead of using zone averages, we used the full set of pixel values within each buffer ring to preserve the paired nature of the data. This was done by converting the clipped rasters to NumPy arrays and calculating r directly using Python 3.11 within ArcGIS Pro 3.4.0. The resulting r values range from -1 to $+1$, with the sign indicating direction and the absolute value indicating strength. To assess statistical significance, we performed two-tailed t -tests using the formula:

$$t = r \times \sqrt{\frac{n-2}{1-r^2}} \quad (5)$$

with degrees of freedom = $n - 2$, where n is the number of valid pixel pairs. The p -values were then derived from the t -distribution.

Linear regression. We modelled LST as a function of NDVI and separately as a function of NDBI. For each zone and year, the slope (b) and intercept (a) of the regression line ($Y = a + bX$) were calculated from the summary statistics using:

$$b = r \times \frac{SD_Y}{SD_X}, a = \bar{Y} - b \times \bar{X} \quad (6)$$

where r is the Pearson correlation, SD is the standard deviation, and $\bar{Y}$ and $\bar{X}$ are the means of the dependent and independent variables, respectively. The coefficient of determination (R^2) was taken as r^2 . This method yields exactly the same coefficients as ordinary least squares regression on the full pixel data, but it is computationally more efficient given the large number of pixels. The results are presented in Table 2a,b and (optionally) Table 2c.

3.5.2. Cross-Validation with MODIS LST

To assess the accuracy of our Landsat-derived LST, we compared it with the MODIS Terra LST product (MOD11A2, version 6.1) for the years 2015, 2018 and 2022. MODIS data were not available for 2026 because the acquisition dates coincided with persistent cloud cover and poor-quality flags ($QC_Day > 0$). For each of the three available years, we extracted MODIS LST values (LST_Day_1 km band, converted from Kelvin to Celsius)

at 500 random points located inside the Addis Ababa boundary. At the same points, we extracted Landsat LST from the corresponding year. After removing points with no data, we computed three validation metrics: the Pearson correlation (r), the root-mean-square error (RMSE) and the mean bias (average difference Landsat minus MODIS). Strong agreement between the two datasets would support the reliability of our Landsat LST retrieval method.

Table 2. (a) Linear regression results for NDVI as a predictor of LST ($LST = a + b \cdot NDVI$) for each year and buffer zone; (b) Linear regression results for NDBI as a predictor of LST ($LST = a + b \cdot NDBI$) for each year and buffer zone; (c) Linear regression results for NDVI as a predictor of NDBI ($NDBI = a + b \cdot NDVI$) for each year and buffer zone.

(a)				
Year	Zone (m)	Slope (b)	Intercept (a)	R ²
2015	0–250	−38.65	37.94	0.405
2015	250–500	−42.12	38.79	0.401
2015	500–1000	−43.62	38.94	0.401
2018	0–250	−28.95	31.44	0.271
2018	250–500	−37.16	33.08	0.31
2018	500–1000	−37.33	33	0.31
2022	0–250	−26.53	35.57	0.264
2022	250–500	−29.18	36.52	0.243
2022	500–1000	−29.64	36.51	0.243
2026	0–250	−29.1	33.51	0.351
2026	250–500	−33.52	34.57	0.375
2026	500–1000	−35.72	34.23	0.375
(b)				
Year	Zone (m)	Slope (b)	Intercept (a)	R ²
2015	0–250	49.74	31.97	0.447
2015	250–500	55.44	31.47	0.446
2015	500–1000	58.07	31.27	0.446
2018	0–250	34.99	28.51	0.287
2018	250–500	45.44	29.16	0.346
2018	500–1000	47.09	29.02	0.346
2022	0–250	33.48	32.66	0.26
2022	250–500	39.78	33.26	0.281
2022	500–1000	39.57	33.12	0.281
2026	0–250	20.06	30.67	0.422
2026	250–500	21.77	31	0.428
2026	500–1000	23.53	30.49	0.428
(c)				
Year	Zone (m)	Slope (b)	Intercept (a)	R ²
2015	0–250	−0.732	0.0715	0.81
2015	250–500	−0.723	0.0745	0.816
2015	500–1000	−0.719	0.0746	0.816
2018	0–250	−0.737	0.0724	0.748
2018	250–500	−0.739	0.076	0.748
2018	500–1000	−0.74	0.0769	0.748
2022	0–250	−0.697	0.0724	0.781
2022	250–500	−0.698	0.0773	0.756
2022	500–1000	−0.698	0.0791	0.756
2026	0–250	−0.664	0.0476	0.691
2026	250–500	−0.717	0.0712	0.671
2026	500–1000	−0.667	0.0658	0.671

4. Results

4.1. Spatial Distribution Patterns

4.1.1. Spatial Pattern of NDVI

The spatial distribution of the Normalised Difference Vegetation Index (NDVI) across Addis Ababa shows a clear difference between the city centre and periphery, with the Kebena River corridor being the most prominent linear feature of higher vegetation density. Figure 2a (2015) indicates that the highest NDVI values (dark green, >0.30) are located in the northern hills, along the eastern escarpment, and in scattered patches in the southwestern part of the city. The central and southern districts of the city, where built-up areas are concentrated, show low NDVI values (0.00 – 0.10 , tan to light green), indicating sparse vegetation or bare soil. By 2026, the pattern is generally similar but with a slight NDVI decline visible across many areas of the city (Figure 2b). The dark green areas are somewhat smaller, and the transition zones (0.10 – 0.20) have become more fragmented. Significantly, the Kebena River corridor continues to have higher NDVI than the immediate surrounding areas, especially within the 0 – 250 m buffer. This persistent strip of greener land indicates that the river environment is capable of supporting vegetation even in otherwise heavily urbanised zones. However, the slight reduction in NDVI along the corridor between 2015 and 2026 indicates increased pressure from surrounding development.

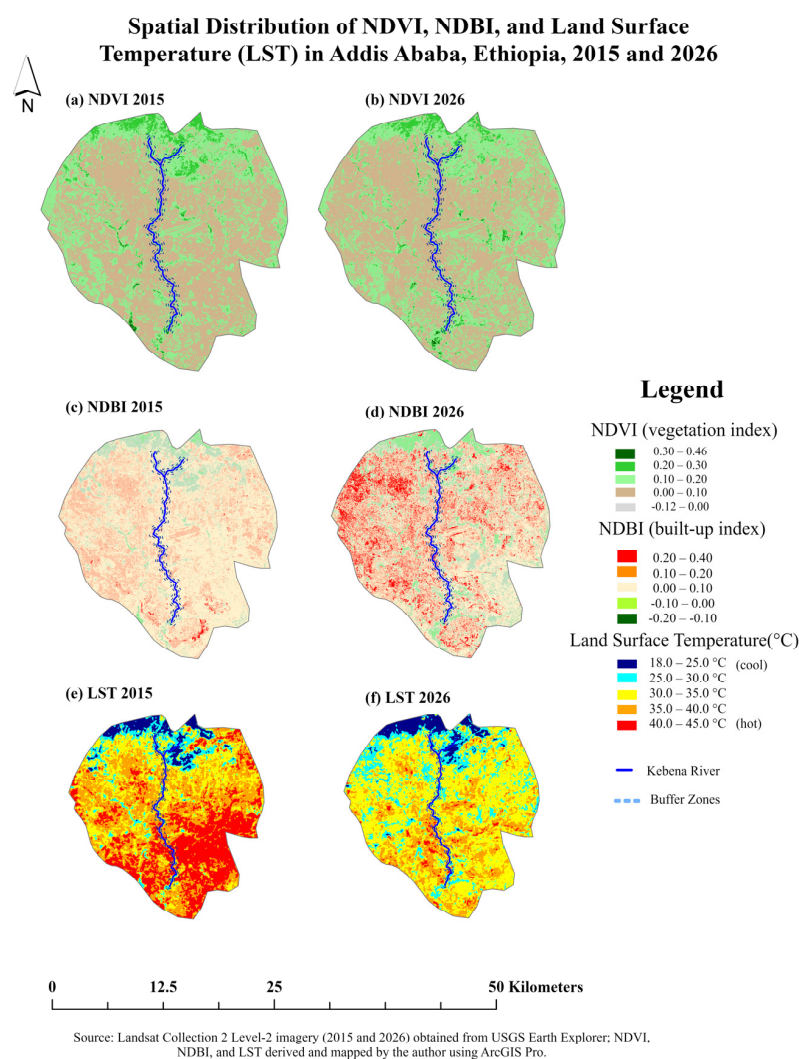


Figure 2. Spatial distribution of (a) NDVI 2015, (b) NDVI 2026, (c) NDBI 2015, (d) NDBI 2026, (e) LST 2015 (°C), and (f) LST 2026 (°C).

4.1.2. Distribution of LST in Space

Land surface temperature in Addis Ababa shows a strong spatial gradient following the distribution of built-up areas and vegetation. In 2015 (Figure 2c), the coolest areas (dark blue, 18–25 °C) occur in the forested hills north of the city and along the Kebena River corridor, where tree cover and moisture help to keep surface temperatures lower. The hottest areas (orange to red, 35–45 °C) are the central business district, industrial zones and densely populated residential areas with little vegetation. In 2026 (Figure 2d), the thermal pattern has intensified: the highest temperature class (40–45 °C) has expanded outwards, and the cool corridor along the Kebena River has contracted. Yet the river itself is still noticeably cooler than the surrounding urban matrix, which suggests that its moderating effect persists even with enhanced warming. The hot surface increase is most prominent in the southern and eastern areas of the city, where recent development has changed agricultural land into built-up areas.

4.1.3. Spatial Distribution of NDBI

The Normalised Difference Built-up Index (NDBI) maps confirm that the intensity of built-up is highest in the city centre and along major transport corridors, with a clear gradient away from the Kebena River. In 2015 (Figure 2e), the highest NDBI values (red, 0.10–0.50) are observed in the central districts, whereas the river corridor and the northern hills show negative values (green, −0.50 to −0.10), indicating low built-up cover. The intermediate zones (250–500 m and 500–1000 m) have transitional NDBI values close to zero (grey), suggesting a mix of buildings, roads and open spaces. By 2026, areas of positive NDBI had expanded across several parts of Addis Ababa, particularly in the western, northern, and peripheral urban sectors, indicating an intensification of the built-up spectral signal at the city scale. However, the Kebena River corridor continued to display predominantly negative NDBI values. Visual comparison of the two annual maps alone does not clearly identify where increases and decreases occurred; therefore, a separate Δ NDBI map was produced to directly represent the spatial difference between 2015 and 2026.

4.1.4. Spatial Change in Built-Up Intensity, 2015–2026

Figure 3 presents the spatial distribution of NDBI change across Addis Ababa between 2015 and 2026. Positive Δ NDBI values represent increased built-up intensity, negative values represent a reduced built-up signal, and values close to zero indicate little detectable change. The city-wide pattern is spatially heterogeneous: moderate and strong increases occur across substantial parts of Addis Ababa, while decreases are concentrated in several northern, southeastern, and river-adjacent locations. This contrast shows that broad urban intensification occurred simultaneously with localised reductions in built-up intensity.

Within the Kebena River corridor, the Δ NDBI pattern includes both increases and decreases, but localised negative values are evident along several river sections. This pattern is consistent with the more negative mean NDBI recorded in the 0–250 m zone in 2026 compared with 2015. Nevertheless, Δ NDBI is a spectral change indicator rather than a direct building-demolition map; decreases may reflect removal of structures, vegetation recovery, changes in exposed soil or moisture, or other land-cover transitions. The result is therefore interpreted as evidence of a localised reduction in the built-up signal within a city that otherwise experienced widespread urban intensification.

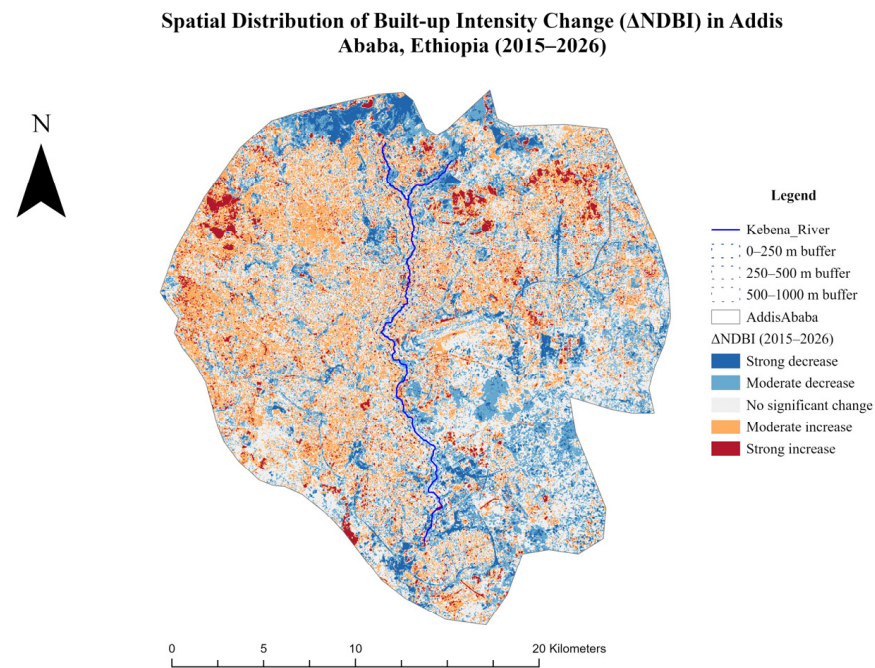


Figure 3. Spatial distribution of Δ NDBI (2015–2026) in Addis Ababa, showing increases and decreases in built-up intensity relative to the Kebeba River corridor.

4.2. Spatial Variation of Environmental Indicators Across Buffer Zones

To quantify the distance-dependent influence of the Kebeba River, we extracted mean values and standard deviations of NDVI, LST and NDBI for each buffer zone and each year. The results are summarised in Table 1. Every year, the 0–250 m zone shows the highest NDVI (e.g., 0.129 in 2015) and the most negative NDBI (e.g., -0.023 in 2015), indicating denser vegetation and lower built-up intensity closest to the river. Conversely, LST is lowest in the 0–250 m zone (32.9°C in 2015) and increases steadily with distance. The 250–500 m and 500–1000 m zones have very similar mean values, suggesting that the corridor’s influence is strongest within the first 250 m and then levels off. Standard deviations are generally similar across zones, meaning that the internal variability of each index does not change dramatically with distance. The NDVI of the 0–250 m zone decreased with time (0.129 in 2015 to 0.120 in 2026) while the mean NDBI became more negative (-0.023 to -0.032). The mean NDVI within the 0–250 m buffer decreased by about 7% from 2015 to 2026, but the decrease has to be seen in the light of the rapid urbanisation of Addis Ababa during the same period. Previous remote sensing studies have consistently shown a decrease in urban vegetation as a consequence of the expansion of built-up areas and increasing development pressure across the city. Thus, the decrease in vegetation in the Kebeba River corridor is in line with the trends of the city in general. However, the corridor still remained an important urban green corridor, indicating that it had relatively higher vegetation cover than much of the surrounding built-up environment, despite this overall reduction. This latter pattern is consistent with the localised decreases seen in the Δ NDBI map in Figure 4 and inconsistent with the widespread increases in built-up intensity observed elsewhere in Addis Ababa. LST shows interannual variability, with 2018 being notably cooler than other years, a likely consequence of the specific acquisition date rather than a long-term trend.

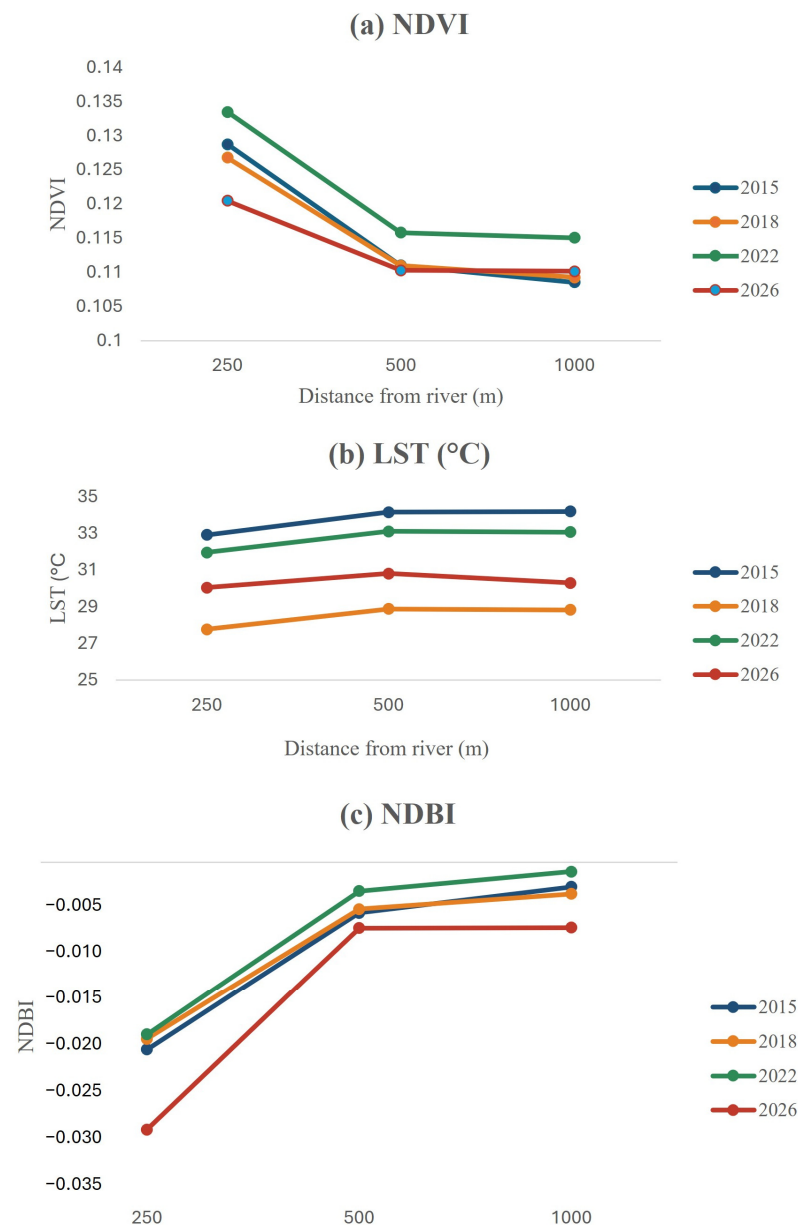


Figure 4. Spatial gradients of (a) NDVI, (b) LST (°C), and (c) NDBI across buffer zones (250 m, 500 m, 1000 m) for the years 2015, 2018, 2022 and 2026.

4.3. Spatial Gradient Across Buffer Zones

The spatial gradient is visualised in Figure 3, which plots mean NDVI, LST and NDBI against distance from the river for each year.

NDVI (Figure 4a) declines sharply from the 0–250 m zone to the 250–500 m zone, after which it remains nearly flat. This pattern holds across all four years, confirming that the river corridor supports measurably more vegetation only within a narrow band of about 250 m. LST (Figure 4b) shows the opposite behaviour: temperatures are lowest at 250 m and rise by roughly 1–2 °C at 500 m, with little further increase beyond that distance. The 2018 line lies consistently below the others, reflecting the cooler conditions of that acquisition, but the shape of the gradient (steep increase, then plateau) is identical to other years. NDBI (Figure 4c) also follows a gradient: values are most negative (least built-up) at 250 m and become progressively less negative (more built-up) at 500 m and 1000 m. Taken together, the panels confirm a consistent distance-decay pattern across all three indicators.

4.4. Temporal Trends in the 0–250 m Zone

Figure 5 focuses on the immediate corridor (0–250 m) to reveal how vegetation, temperature and built-up intensity have changed over the eleven-year study period. Figure 5a shows that NDVI fluctuated between 2015 and 2022, rising slightly from 0.129 to 0.133, before falling to 0.120 in 2026.

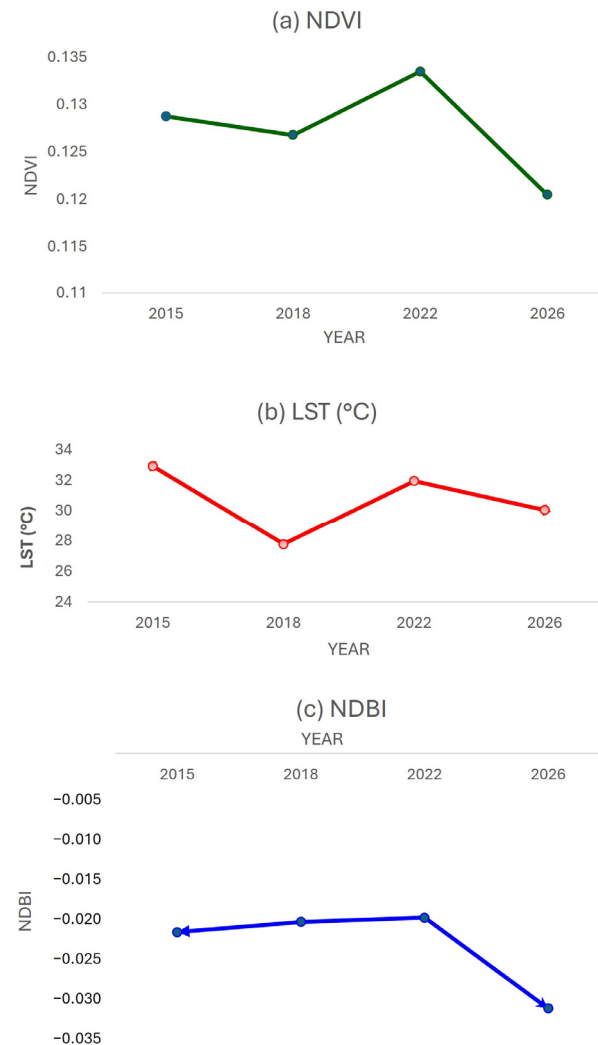


Figure 5. Temporal trends of (a) NDVI, (b) LST (°C), and (c) NDBI in the 0–250 m buffer zone (immediate Kebena River corridor) from 2015 to 2026.

Figure 5b shows a markedly lower LST in 2018 (27.8 °C) than in the other study years; this anomaly is examined in Section 5.5. Leaving aside the 2018 anomaly, LST in 2026 (30.0 °C) is slightly lower than in 2015 (32.9 °C) and 2022 (32.0 °C), which may reflect interannual variability or local land-cover changes that are not captured by the four time points.

Figure 5c shows the Temporal NDBI pattern in the 0–250 m zone. NDBI was negative during the entire study period, which confirms that the built-up signal in the immediate corridor was always weaker than in the surrounding urban environment. Urban intensification is widespread throughout Addis Ababa, but the mean NDBI changed from −0.023 in 2015 to −0.032 in 2026. This zone-level result is consistent with the localised negative Δ NDBI values presented in Figure 3. The timing of the decline also matches documented rehabilitation efforts along sections of the Kebena corridor between 2022 and 2025. However, given the absence of a control corridor or a building inventory from the field, the

observed reduction should be understood as temporally consistent with the intervention, and not definitive proof of causation.

To quantify the strength of the relationships among the three indices, we calculated Pearson correlation coefficients for each year and each buffer zone using all pixel values ($n > 16,000$ per zone). All correlations were statistically significant at $p < 0.001$, as expected given the large sample sizes.

NDVI and LST were consistently negatively correlated, with r values ranging from -0.49 to -0.64 . The strongest negative correlations occurred in the 0–250 m zone of 2015 ($r = -0.636$) and the weakest in the 250–500 m zone of 2022 ($r = -0.493$). This confirms that areas with denser vegetation are significantly cooler, and the effect is most pronounced near the river.

NDBI and LST showed positive correlations, with r values between 0.51 and 0.67 . The highest positive correlation was found in the 0–250 m zone of 2015 ($r = 0.668$), indicating that built-up intensity and temperature rise together. As with the NDVI-LST relationship, the strength of the correlation tended to be slightly higher in the inner zone than in the outer zones.

NDVI and NDBI exhibited strong negative correlations, with r values between -0.83 and -0.90 . The near-perfect negative relationship ($r = -0.90$ in many zones) reflects the spatial opposition of vegetation and built-up land: where one is high, the other is low. This tight coupling underscores the importance of preserving vegetation to limit built-up expansion along the corridor.

All correlation values, together with their sample sizes and p -values, are provided in the Supplementary Materials (Table S1). The consistently significant correlations across all years and zones demonstrate that the three indices form a tightly linked system, with the Kebena River corridor acting as a local modifier of that system.

4.5. Regression Analysis

To move beyond correlation and quantify how much LST changes per unit change in NDVI or NDBI, we fitted linear regression models for each year and buffer zone. The results are summarised in Table 2a–c.

NDVI as a predictor of LST (Table 2a). NDVI as a predictor of LST. (Table 2a). All the slopes were negative, meaning that as NDVI increased, LST decreased. In the 0–250 m zone, the slope varied from -26.5 (2022) to -38.7 (2015), meaning that a 0.1 increase in NDVI led to a decrease in LST of about 2.7 °C to 3.9 °C. The steepest gradients were found in the outer zones (500–1000 m: -43.6) in 2015, indicating that the cooling effect per unit vegetation is actually stronger further away from the river despite the lower total vegetation density. Intercepts (corresponding to LST at NDVI = 0) ranged from 31.4 °C (2018) to 38.9 °C (2015). R^2 values ranged from 0.24 to 0.41 , indicating that NDVI alone explains between a quarter and two-fifths of the variance in LST—a moderate but meaningful influence.

NDBI as a predictor of LST (Table 2b). All slopes were positive, as expected: increasing built-up intensity raises surface temperature. In the 0–250 m zone, slopes varied from 20.1 (2026) to 49.7 (2015). A 0.1-unit increase in NDBI (moving from -0.02 to $+0.08$, for example) would raise LST by approximately 2.0 °C to 5.0 °C. The strongest warming effect per unit NDBI was found in the 500–1000 m zone of 2015 (slope = 58.1), again suggesting that built-up expansion in outer zones may have a larger thermal impact per unit than infill near the river. Intercepts ranged from 28.5 °C (2018) to 33.1 °C (2022). R^2 values (0.26 – 0.45) were similar to those for NDVI, confirming that both vegetation and built-up intensity are important but not exclusive drivers of LST.

NDVI as a predictor of NDBI (Table 2c). This additional regression quantifies the spatial opposition between vegetation and built-up land. All slopes were negative and steep,

ranging from -0.66 to -0.74 . In the 0–250 m zone, a 0.1-unit increase in NDVI corresponded to a decrease in NDBI of about 0.07, meaning that denser vegetation strongly suppresses built-up intensity. Intercepts (the predicted NDBI when NDVI is zero) fell between 0.047 and 0.079, indicating that in the absence of vegetation, NDBI would be slightly positive (built-up-dominated). R^2 values were remarkably high (0.67–0.82), showing that NDVI alone explains most of the spatial variation in NDBI—a clear demonstration of the tight coupling between vegetation and urbanisation.

Taken together, the regression results provide a quantitative basis for the spatial gradients observed earlier. They confirm that the Kebena River corridor moderates both temperature and built-up intensity through its vegetation, but the strength of this moderation varies by distance and has shifted over time.

5. Discussion

5.1. The Kebena River Corridor as a Persistent Vegetation and Cooling Gradient

The results leave little doubt that the Kebena River corridor functions as a localised green and cool island within Addis Ababa's urban fabric. The persistent inner-zone advantage indicates that the Kebena River functions as a localised green–blue climatic corridor within Addis Ababa. Riparian areas typically retain soil moisture longer than upland sites, which supports denser vegetation even during the dry season. The vegetation itself then amplifies the cooling effect through evapotranspiration and shading, creating a positive feedback loop that keeps the corridor relatively cool.

The shape of the spatial gradient (steep decline in NDVI and increase in LST from 250 m to 500 m, then a plateau) was virtually identical in 2015, 2018, 2022 and 2026. This stability suggests that the river's influence is structurally embedded in the urban landscape—it is not easily erased by short-term weather fluctuations or minor land cover changes. From a planning perspective, this is both encouraging and cautionary. It is encouraging because it shows that even a relatively narrow river corridor can maintain a measurable environmental benefit despite decades of urban expansion. It is cautionary because the gradient is confined to a narrow band (roughly 250 m), beyond which the river's effect becomes indistinguishable from the background urban condition.

The cooling effect observed here is consistent with previous studies of urban river corridors in other climatic contexts. For example, research in Seoul, Shanghai and Phoenix has reported temperature reductions of 1–3 °C within 100–200 m of rivers, with the influence diminishing rapidly beyond that distance. Our results align with those findings, though the absolute cooling magnitude (1–2 °C between the 0–250 m and 500–1000 m zones) is modest. This modest magnitude may reflect the relatively small size of the Kebena River and the fact that its banks are not uniformly vegetated; there are stretches where informal settlements or infrastructure encroach directly on the watercourse. Nevertheless, the fact that a statistically significant gradient exists at all, across four separate years, underscores the value of protecting even narrow riparian strips in dense cities.

River corridors not only moderate urban temperature but also provide important ecological functions that support urban conservation. Riparian vegetation supports habitat for birds, insects, and small mammals and plays a role in maintaining ecological connectivity across increasingly fragmented urban landscapes. These ecological functions enhance ecosystem resilience, sustain biodiversity and contribute to the long-term sustainability of cities. The continued cooling and greening effects observed along the Kebena River thus underscore its climatic importance and its conservation value. The protection and restoration of urban river corridors should be considered as a long-term investment to maintain ecosystem services and improve resilience in fast urbanising cities.

5.2. Comparison with Other Urban River Corridor Studies

The environmental patterns reported along the Kebena River are generally consistent with those reported from other urban river corridors worldwide. However, the results also reflect the specific environmental conditions, rapid urbanisation and restoration efforts that typify Addis Ababa, making the corridor an important example of urban river conservation in Sub-Saharan Africa.

River corridors as persistent cool islands. The fact that the Kebena corridor remains cooler and greener than its surroundings, despite ongoing urban expansion, aligns with a growing body of evidence from other cities. Studies in Shanghai, for instance, have shown that riparian buffers along urban rivers create strip-shaped “cold zones” within high-temperature urban matrices [31], with cooling effects that are measurable even when the river itself is narrow. Similarly, research on the Minxin River in Shijiazhuang found that the average surface temperature of the river was notably lower than that of the surrounding built-up area [32], producing a linear cooling feature that persisted across different segments of the river. These examples echo our finding that the Kebena River stands out as a continuous cool strip in an otherwise warming urban landscape.

Distance-dependent cooling and its limits. The spatial gradient we observed was sharpest within the first 250 m, then levelled off, mirroring results from other river cooling studies. In Shijiazhuang, the average cooling distance of the Minxin River was 165 m [32], beyond which surface temperature rose rapidly and then stabilised. A more recent synthesis of 27 riparian green spaces in Zhengzhou reported an average cooling distance of 215 m, with cooling intensities of around 5.4 °C [33]. Our finding that the cooling influence of the Kebena corridor is largely confined to the 0–250 m buffer is therefore consistent with a wider international pattern: river cooling is real, but its reach is limited, and does not extend far beyond the immediate riparian zone. This limited spatial footprint has important implications for planning: protecting a narrow strip alone may not be sufficient to influence thermal conditions across whole neighbourhoods.

The role of vegetation versus water. A nuance in the literature is whether the cooling effect of a river corridor is primarily due to the water body itself or to the vegetation that grows alongside it. In Antakya, Turkey, researchers found that the cooling impact of blue corridors was more closely tied to dense vegetation than to the mere presence of water; where riparian vegetation was sparse [34], the cooling effect was limited. Our results support this emphasis on vegetation. The NDVI-LST correlations we observed (r values between -0.49 and -0.64) indicate that vegetated surfaces along the Kebena corridor contribute meaningfully to temperature reduction. This is consistent with the broader principle that evapotranspiration from plants, not just the water surface, drives much of the cooling. The ecological importance of riparian vegetation extends beyond temperature regulation. Healthy vegetation along riverbanks enhances habitat quality, supports pollinators and urban wildlife, reduces soil erosion, and increases ecological connectivity between fragmented green spaces. Therefore, the preservation of riparian vegetation simultaneously promotes the conservation of biodiversity, the durability of the ecosystem and the adaptation of urban climate. The multiple ecosystem services emphasise the need to conserve urban river corridors as an integral component of sustainable cities.

Evidence from other African cities. Although the number of studies on urban river corridors has increased worldwide, empirical evidence from Sub-Saharan Africa remains scarce. This underscores the necessity of studies such as the present research that provide locally relevant evidence to understand the environmental and conservation benefits of urban river systems under rapid urbanisation. A recent analysis of blue-green infrastructure in four East African cities (Khartoum, Addis Ababa, Kampala, and Dar es Salaam) confirmed that urban green and blue spaces can moderate surface urban heat island intensity, though

the effectiveness varied by local climate zone and season. Within Addis Ababa itself, a study of the Piassa–Megenagna corridor found that NDVI declined consistently from 2015 to 2024 (from 0.345 to 0.200), while NDBI increased over the same period, pointing to a general trend of vegetation loss and built-up expansion. Our results for the Kebena corridor show a similar but more modest decline in NDVI (from 0.129 in 2015 to 0.120 in 2026), which may reflect the protective effect of the river environment slowing but not halting vegetation loss.

What makes this study distinctive. Unlike many earlier studies that have focused on individual large parks, lakes or wide rivers, our work centres on a relatively narrow urban river corridor in a fast-growing African city. The use of a multi-buffer approach (250 m, 500 m, 1000 m) combined with pixel-wise correlation and regression provides a more detailed quantification of the distance-decay pattern than coarser city-scale analyses. Moreover, the inclusion of four time points (2015–2026) allows us to detect not only the spatial gradient but also its gradual weakening under urban pressure, a temporal dimension that is still rare in the literature on river corridors in the Global South. This study not only shows the environmental benefits of the Kebena River corridor but also provides evidence for the conservation and restoration of urban riparian ecosystems. The results suggest that the preservation of vegetation along river corridors helps to mitigate thermal stress in addition to the conservation of important ecological functions within densely populated cities. As many African cities continue to grow, the importance of integrating river corridor conservation into urban planning strategies will only grow for the continued maintenance of biodiversity, ecosystem services, and climate resilience. In this sense, the Kebena corridor can be seen as a microcosm of a broader tension: riparian green spaces offer tangible local benefits, but those benefits are steadily eroded unless actively protected and expanded. The observed decline in NDVI is also consistent with broader vegetation changes reported across Addis Ababa. Previous studies have shown that continued urban expansion has resulted in the gradual conversion of vegetated land into built-up areas throughout the city. Compared with these city-wide trends, the reduction observed along the Kebena River corridor is relatively moderate, suggesting that the riparian environment has slowed, but not completely prevented, vegetation loss [9,35]. These findings highlight both the ecological importance of the corridor and the need for continued conservation and restoration measures to preserve its environmental functions.

5.3. The Coupled System: NDVI, LST and NDBI as Interdependent Variables

One of the key findings of this study is that vegetation cover, land surface temperature, and built-up intensity act as an integrated environmental system rather than independent indicators. The Kebena River corridor plays an important role in managing these interactions through the vegetation, limiting the expansion of built-up surfaces. The consistently negative correlations between NDVI and LST ($r \approx -0.5$ to -0.6) and between NDVI and NDBI ($r \approx -0.8$ to -0.9), together with the positive correlations between NDBI and LST ($r \approx 0.5$ to 0.7), demonstrate that where vegetation is denser, temperatures are lower and built-up cover is sparser. Conversely, where built-up intensity rises, vegetation declines and temperatures increase.

This coupling is not merely statistical; it reflects causal processes that are well understood in urban climate science. Vegetated surfaces reduce temperature through evapotranspiration and shading, and they also tend to occupy spaces that are less suitable or less accessible for construction—such as steep slopes, floodplains, or protected green corridors. Built-up surfaces, in contrast, store and release heat, suppress evapotranspiration, and are typically placed on flatter, more accessible land. The river corridor, by virtue of its topography and moisture availability, favours vegetation and discourages dense construction,

thereby creating a local decoupling of the otherwise strong urbanisation-heating link. Our regression results quantify this decoupling: in the 0–250 m zone, a 0.1-unit increase in NDVI lowers LST by roughly 2.7–3.9 °C, whereas the same increase in NDBI raises LST by 2.0–5.0 °C. The fact that these slopes are steeper in the outer zones (500–1000 m) suggests that when vegetation or built-up does appear far from the river, its per-unit thermal effect is actually larger—but because vegetation density is already low there, the net impact remains small.

From a planning perspective, the tight coupling implies that interventions aimed at one variable will inevitably affect the others. The strong interaction between vegetation, built-up intensity, and surface temperature also points to the importance of integrated conservation strategies. River corridor conservation should be considered a multifunctional approach providing ecological, climatic and social benefits all at once, rather than as individual issues of vegetation management, urban development and climate adaptation. Healthy riparian vegetation improves habitat quality, enhances ecological connectivity, reduces urban heat stress, and increases ecosystem resilience. Planting trees along the river will not only increase NDVI but also lower LST and, if done strategically, may discourage adjacent construction by enhancing the perceived value of green space. Conversely, allowing unregulated development within the 0–250 m buffer will simultaneously reduce NDVI, raise LST and increase NDBI, accelerating the very environmental degradation that the corridor currently mitigates.

5.4. Temporal Weakening of Corridor Functions Under Urban Pressure

While the spatial gradient along the Kebena corridor remained structurally intact across all four study years, the temporal trends reveal a slow but consistent erosion of the corridor's environmental benefits. NDVI in the 0–250 m zone declined from 0.129 in 2015 to 0.120 in 2026, a net loss of roughly 7%. This decline is not dramatic, but it is statistically significant given the large number of pixels involved, and it suggests that even the immediate riverbank is not entirely insulated from the city's expansion. The fact that the decline occurred despite the corridor's natural moisture advantage is a warning sign: if urban pressure can reduce vegetation directly alongside the river, the outer zones are likely to be even more affected.

The NDBI trend in the 0–250 m zone requires a different interpretation. Instead of moving toward zero (which would indicate increasing built-up intensity), NDBI became slightly more negative, from −0.023 in 2015 to −0.032 in 2026. As explained in Section 5.5, this is not a puzzling anomaly but a direct consequence of the Kebena River Corridor Project (2022–2025), which removed informal settlements from the immediate riverbanks. The project demonstrates that deliberate policy intervention can reverse built-up encroachment in a short time frame. However, the concurrent decline in NDVI (−7%) shows that vegetation recovery lags behind demolition; simply removing structures does not automatically restore ecological function. The corridor remains under pressure, but the NDBI shift provides a rare empirical example of successful intervention in a rapidly urbanising African city.

LST trends are complicated by the anomalously cool 2018 acquisition, which makes it difficult to discern a clear long-term warming signal. If we compare 2015 (32.9 °C) with 2026 (30.0 °C), the corridor appears to have cooled, which is improbable given regional warming trends. The more reasonable interpretation is that interannual variability in weather and acquisition date overwhelms any modest warming trend over this short period. This underscores a limitation of using only four time points: short-term climate fluctuations can mask or reverse the underlying long-term change. Nevertheless, the fact that NDVI declined while NDBI did not become less negative indicates that the

corridor is not strengthening its role; at best, it is holding steady, and at worst, it is slowly losing vegetation cover. The varying trends of vegetation loss and built-up intensity indicate that ecological restoration is not a one-off event, but a continuous process. The rehabilitation programme has been successful in reducing built-up encroachment along the riverbanks, but maintaining and expanding riparian vegetation will require long-term conservation measures, regular monitoring and sustained management. The long-term protection of the corridor could prevent development pressure from eroding the ecological functions of the corridor and the ability of the corridor to regulate urban temperature and support biodiversity.

What does this mean for urban resilience? The Kebena corridor is not about to disappear overnight. Its physical characteristics—the river itself, the steep banks in some stretches, the residual soil moisture—will continue to support vegetation and moderate temperature for the foreseeable future. But the trend lines suggest that without deliberate protection, the corridor's effectiveness will continue to diminish. The 7% decline in NDVI over eleven years, if extrapolated, would lead to a halving of riparian vegetation density within roughly a century. That may sound slow, but in a city that is growing as fast as Addis Ababa, even gradual losses accumulate into significant degradation over a generation. The temporal weakening is therefore not a crisis but a chronic condition, one that calls for proactive planning rather than emergency intervention.

5.5. Explanation of the 2018 LST Anomaly and the 2026 NDBI Shift

The 2018 LST anomaly. In the 0–250 m zone, mean LST was 27.8 °C in 2018, compared with 32.9 °C in 2015, 32.0 °C in 2022 and 30.0 °C in 2026. The most plausible explanation is that the 2018 Landsat acquisition (13 January) occurred during a cooler spell than the other dates. While all images were selected from the dry season, January can be noticeably cooler than February or March in Addis Ababa, especially in years with stronger highland winds or cloud cover. The MODIS validation for 2018 also showed a lower value (30.1 °C) compared to Landsat (29.5 °C), but both were lower than in other years. This consistency suggests that the anomaly is real in the satellite record, not a processing error. Importantly, the spatial gradient (the difference between the 0–250 m zone and the outer zones) remained intact in 2018, which indicates that the relative influence of the corridor was unchanged even though absolute temperatures were lower. Thus, while the anomaly complicates the interpretation of long-term temperature trends, it does not undermine the core finding about the corridor's spatial effect.

And this change also coincides with the timing of the Kebena River Corridor Project, which is implemented from 2022 to 2025. This apparent reduction in built-up intensity is not a sensor artefact, atmospheric condition, or soil moisture effect. Instead, it reflects a real, on-the-ground change: the Kebena River Corridor Project, carried out between 2022 and 2025. The project involved the relocation of informal settlements that had long occupied the riverbanks, followed by basic riparian rehabilitation (removal of debris, grading, and limited planting). The removal of built-up structures directly lowered the NDBI signal in the 2026 Landsat image. Although direct field verification was beyond the scope of this study, the interpretation of the 2026 decrease in NDBI is supported by publicly available information on the Kebena River rehabilitation programme, which is part of Addis Ababa's Sheger Riverside Development Project. This project included the removal of informal structures in the river corridor, the stabilisation of the riverbank, the restoration of riparian vegetation, the improvement of drainage infrastructure, and the development of public green spaces [9]. This interpretation is further corroborated by the city-wide Δ NDBI map. While large parts of Addis Ababa exhibited moderate to strong increases in built-up intensity between 2015 and 2026, there were several parts of the Kebena

corridor which showed reduced NDBI values (Figure 3). This spatial contrast implies that the corridor followed a locally different path from the broader city. The coincidence of these reductions with the documented rehabilitation period increases the plausibility for an intervention-related effect, although other factors, including vegetation change, soil exposure, moisture conditions, and image-date variability, may also be influencing the NDBI signal. These interventions reduced the extent of built-up land adjacent to the river and provided a reasonable explanation for the reduced NDBI values observed in 2026, but continued monitoring will be necessary to evaluate the long-term environmental impact of the rehabilitation scheme.

5.6. Limitations

Spatial resolution and mixed pixels. Landsat's 30 m resolution means that many pixels contain a mixture of vegetation, bare soil and built-up materials. This is especially problematic in the narrow buffer zones, where a single pixel may straddle the riverbank and a road. While the large number of pixels mitigates the impact of misclassification, fine-scale features such as narrow tree lines or small buildings are inevitably smoothed. Higher-resolution data (e.g., Sentinel-2 at 10 m or commercial imagery) would provide a more detailed view, but at the cost of shorter temporal archives.

Temporal sampling. The study uses only four time points over eleven years. This sparse sampling cannot capture interannual variability in rainfall, land management or construction activity. The 2018 LST anomaly, for instance, would have been less conspicuous if we had data for 2019 or 2020. A denser time series (e.g., every two years) would give a more robust picture of trends, but it would also increase the data-processing burden.

Validation. We cross-validated Landsat LST with MODIS for 2015, 2018, and 2022, but we could not include 2026 because of poor MODIS data quality. While the three-year validation gave good metrics (RMSE = 1.04 °C, bias = +0.49 °C), we have no independent check on the 2026 LST values. In situ temperature measurements from weather stations or field campaigns would provide stronger validation, but such data were not available for this study.

Single-corridor case study. The Kebena River is one of several waterways in Addis Ababa, and our findings may not be directly transferable to other corridors with different widths, vegetation cover or surrounding land uses. A broader generalisation would require a multi-corridor analysis covering the entire urban river network.

Indices and their ambiguities. NDVI, LST and NDBI are well-established proxies, but each has limitations. NDVI saturates in very dense vegetation, LST is affected by atmospheric moisture and viewing angle, and NDBI can confuse bare soil with built-up surfaces. Using additional indices (e.g., Enhanced Vegetation Index, Normalised Difference Water Index) might refine the analysis, but that would extend the scope beyond the current research questions. Nevertheless, the 2026 NDBI decrease along the Kebena corridor was independently confirmed by the known removal of informal settlements under the Kebena River Corridor Project, which reduces the likelihood of spectral confusion in this specific case.

Human and policy factors. The study is purely geospatial; it does not incorporate socio-economic data such as land ownership, building permits, or population density. These factors are likely important drivers of the observed changes, but they lie outside the remote-sensing focus of this paper. Integrating social and physical data is a natural next step. Another limitation is the absence of a comparable urban river corridor that was not rehabilitated during the study period. Thus, while the trends observed along the Kebena River over time are consistent with known rehabilitation activities, the present study cannot separate the effects of such interventions from more citywide environmental

changes. The inclusion of control corridors in future research would provide stronger evidence for evaluating the effectiveness of river restoration programmes.

Another limitation is that the study is mainly focused on remotely sensed environmental indicators. Although NDVI, LST, and NDBI provide useful information about environmental conditions, they do not directly measure ecological characteristics such as species diversity, habitat quality, or ecosystem health. Future studies that couple satellite observations with field-based ecological surveys will allow a more complete assessment of the conservation status of urban river corridors.

5.7. Implications for Urban Conservation, Green-Blue Infrastructure, and Sustainable Management

The findings of this study carry several practical implications for how Addis Ababa—and other rapidly growing cities—might manage river corridors to preserve their environmental benefits.

Protect the narrow but critical buffer. Conserving this riparian buffer will not only preserve its cooling capacity but also maintain ecological connectivity, improve habitat quality, and strengthen ecosystem resilience within the rapidly expanding urban landscape. This means that protecting a relatively narrow strip along the Kebena River can deliver measurable cooling and vegetation benefits. However, the same narrowness implies that the current buffer is vulnerable: a single row of buildings built directly on the riverbank could erase much of the corridor's effect. Urban planners should therefore establish or enforce setback regulations that prevent construction within at least 50–100 m of the river, and ideally preserve the full 250 m as a green belt. Where informal settlements already exist, phased relocation combined with riparian restoration could gradually recover the lost ecological function.

Built-up encroachment can be undone through planned interventions. Rehabilitation programmes should combine settlement relocation, bank restoration, active planting and long-term maintenance. Targeted, well-funded relocation programmes, together with basic restoration, can restore the corridor's ecological and thermal functions. However, the absence of a corresponding NDVI increase by 2026 also warns that vegetation recovery lags behind demolition; therefore, active planting and maintenance must follow immediately after relocation. This evidence can also be used to justify investments in corridor restoration as a viable climate adaptation strategy for other rapidly growing cities facing similar informal settlement pressures along waterways.

Extend green infrastructure beyond the immediate corridor. Because the corridor's influence dissipates rapidly beyond 250 m, relying on the river alone to cool neighbourhoods is insufficient. Planning strategies should use the river as a spine and connect it to a network of smaller green spaces—pocket parks, tree-lined streets, green roofs—that extend the cooling effect deeper into the surrounding blocks. The high negative correlation between NDVI and NDBI (−0.8 to −0.9) implies that any increase in vegetation will likely displace built-up surfaces; thus, creating new green spaces may require acquiring land or incentivising private landowners to retain trees.

Use vegetation as a primary tool for thermal regulation. Investment in riparian tree planting, bank stabilisation with native vegetation, and removal of invasive species would directly enhance this cooling service. Moreover, because vegetation also suppresses NDBI, greening the corridor may indirectly discourage adjacent construction by raising the perceived value of open space.

Monitor trends with repeated remote sensing. This suggests that regular (e.g., biennial) monitoring of the corridor using Landsat or Sentinel-2 could serve as an early warning system. If NDVI continues to fall or NDBI begins to rise toward zero, planners would have objective evidence that current protection measures are inadequate. The methods developed here—zonal statistics, correlation and regression—can be operationalised by the city's environmental department at minimal cost.

Integrate with broader climate adaptation strategies. Also, the successful conservation of urban river corridors needs the active participation of local communities, environmental authorities and urban planners. Restoration projects can be made more effective, and future encroachment on riparian ecosystems can be reduced, through public awareness programmes, community stewardship and long-term environmental monitoring. Collaborative management approaches thus provide an important basis for sustaining conservation outcomes in rapidly urbanising cities. Addis Ababa's urban heat island is likely to intensify under global warming. The Kebena corridor cannot reverse that trend city-wide, but it can provide localised relief for residents in adjacent neighbourhoods. Planners should therefore prioritise the corridor as a "cool corridor" in the city's climate adaptation plan, linking it to public health campaigns (e.g., encouraging walking and cycling along shaded paths) and to emergency heat-wave response (e.g., designating the corridor as a cooling refuge). The 250–500 m and 500–1000 m buffers, while less effective, could still be targeted for medium-density, mixed-use development that preserves some permeability and tree cover, rather than allowing full sealing.

Learn from other cities. Addis Ababa can therefore adopt best practices from those cities—such as integrating river corridors into greenway networks, using permeable materials near riverbanks, and involving local communities in stewardship—while adapting them to the local context of rapid informal growth.

6. Conclusions

This research assessed the effects of the Kebena River corridor on the vegetation cover, land surface temperature, and built-up intensity of Addis Ababa by using multi-temporal Landsat images of 2015, 2018, 2022, and 2026. Results show a consistent environmental gradient created by the river corridor with the highest vegetation cover, the lowest land surface temperature and the lowest built-up intensity within 250 m of the river. Further away, the environmental benefits diminish gradually, indicating that the corridor effect is spatially limited but detectable.

The analysis also showed a strong relationship between vegetation, land surface temperature and built-up intensity. Areas with more vegetation had consistently lower surface temperatures and lower built-up intensity, while the more urbanised areas were generally warmer and less vegetated. The regression analysis also indicated that a small increase in vegetation was associated with a large decrease in land surface temperature, which demonstrated the vital role of riparian vegetation in controlling the urban thermal environment.

The decline in built-up intensity within the 0–250 m buffer, despite the decline in vegetation cover during the study period, indicates that the recent rehabilitation of the Kebena River corridor has already led to a measurable environmental change. These results imply that restoration programmes can be effective in relieving development pressure on urban riparian zones, but that the retention of these benefits will require continued protection and long-term management of riparian vegetation.

From a conservation perspective, the study shows that urban river corridors may have benefits beyond local temperature control. They are important green-blue infrastructure that supports ecological connectivity, enhances ecosystem resilience, and contributes to the conservation of urban biodiversity while improving environmental qualities. Thus, the protection and restoration of riparian corridors should be viewed as a component of sustainable urban development, rather than as an environmental goal in itself.

The methods described in this study provide a practical framework for monitoring environmental change with freely available satellite imagery and are easily transferable to other rapidly urbanising cities. Future research should integrate remote sensing with field-based ecological observations, biodiversity assessments and socio-economic data to better understand the long-term conservation outcomes of urban river restoration. Furthermore, continued monitoring of the Kebena River corridor will be useful for assessing the effectiveness of ongoing restoration efforts and supporting evidence-based decision-making for sustainable urban ecosystems management. Future studies should integrate multi-season satellite observations, field-based ecological surveys and control river corridors to further evaluate the long-term effectiveness of urban river rehabilitation programmes.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/conservation6030091/s1>, Table S1: Pearson correlation coefficients (r), sample sizes (n), and *p*-values for the relationships among NDVI, LST, and NDBI for each study year and buffer zone. Pearson correlation coefficients (r), sample sizes (n), and *p*-values for the relationships among NDVI, LST, and NDBI for each study year and buffer zone.

Author Contributions: Conceptualization, Z.L. and T.H.G.; methodology, T.H.G.; software, T.H.G.; validation, Z.L. and T.H.G.; formal analysis, T.H.G.; investigation, T.H.G.; resources, Z.L.; data curation, T.H.G.; writing—original draft preparation, T.H.G.; writing—review and editing, Z.L. and T.H.G.; visualization, T.H.G.; supervision, Z.L.; project administration, Z.L.; funding acquisition, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 42261046, and the Jiangxi Provincial University Humanities and Social Sciences Research Fund, grant number JC21237.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study are available from the author upon reasonable request.

Acknowledgments: The author would like to acknowledge the United States Geological Survey (USGS) and NASA for providing free Landsat and MODIS satellite data used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Aslam, D.M.; Hussian, D.Z.; Sattar, F.A. Urbanization: A Comprehensive Analysis of Causes, Impacts, and Policy Implications. *Ann. Hum. Soc. Sci.* **2025**, *6*, 61–71. [[CrossRef](#)]
2. Zhou, D.; Xiao, J.; Bonafoni, S.; Berger, C.; Deilami, K.; Zhou, Y.; Frolking, S.; Yao, R.; Qiao, Z.; Sobrino, J.A. Satellite Remote Sensing of Surface Urban Heat Islands: Progress, Challenges, and Perspectives. *Remote Sens.* **2018**, *11*, 48. [[CrossRef](#)]
3. Li, X.; Zhou, W.; Ouyang, Z. Relationship between land surface temperature and spatial pattern of greenspace: What are the effects of spatial resolution? *Landsc. Urban Plan.* **2013**, *114*, 1–8. [[CrossRef](#)]
4. Guha, S.; Govil, H.; Diwan, P. Analytical study of seasonal variability in land surface temperature with normalized difference vegetation index, normalized difference water index, normalized difference built-up index, and normalized multiband drought index. *J. Appl. Remote Sens.* **2019**, *13*, 024518. [[CrossRef](#)]

5. Gunawardena, K.R.; Wells, M.J.; Kershaw, T. Utilising green and bluespace to mitigate urban heat island intensity. *Sci. Total Environ.* **2017**, *584*, 1040–1055. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Addis, T.L.; Birhanu, B.S.; Italemahu, T.Z. Effectiveness of Urban Climate Change Governance in Addis Ababa City, Ethiopia. *Urban Sci.* **2022**, *6*, 64. [\[CrossRef\]](#)
7. Estoque, R.C.; Murayama, Y.; Myint, S.W. Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia. *Sci. Total Environ.* **2017**, *577*, 349–359. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Follmann, A. Geographies of peri-urbanization in the global south. *Geogr. Compass* **2022**, *16*, e12650. [\[CrossRef\]](#)
9. Hailu, T.; Assefa, E.; Zeleke, T. Urban expansion induced land use changes and its effect on ecosystem services in Addis Ababa, Ethiopia. *Front. Environ. Sci.* **2024**, *12*, 1454556. [\[CrossRef\]](#)
10. Chithra, S.V.; Nair, M.H.; Amarnath, A.; Anjana, N.S. Impacts of impervious surfaces on the environment. *Int. J. Eng. Sci. Invent.* **2015**, *4*, 27–31.
11. Mohamed, A.; Lorestani, N.; Shabani, F. Impact of urbanization on land surface temperature: A global perspective. *Curr. Res. Environ. Sustain.* **2025**, *10*, 100315. [\[CrossRef\]](#)
12. Ferrini, F.; Fini, A.; Mori, J.; Gori, A. Role of Vegetation as a Mitigating Factor in the Urban Context. *Sustainability* **2020**, *12*, 4247. [\[CrossRef\]](#)
13. Qiu, G.-Y.; Li, H.-Y.; Zhang, Q.-T.; Chen, W.; Liang, X.-J.; Li, X.-Z. Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture. *J. Integr. Agric.* **2015**, *12*, 1307–1315.
14. Huang, S.; Tang, L.; Hupy, J.P.; Wang, Y.; Shao, G.F. A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *J. For. Res.* **2021**, *32*, 1–6. [\[CrossRef\]](#)
15. Dutta, D.; Rahman, A.; Paul, S.K.; Kundu, A. Spatial and temporal trends of urban green spaces: An assessment using hyper-temporal NDVI datasets. *Geocarto Int.* **2022**, *37*, 7983–8003. [\[CrossRef\]](#)
16. Weng, Q. Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. *ISPRS J. Photogramm. Remote Sens.* **2009**, *64*, 335–344. [\[CrossRef\]](#)
17. Zhang, M.; Yiğit, İ.; Adigüzel, F.; Hu, C.; Chen, E.; Siyavuş, A.E.; Elmastaş, N.; Ustuner, M.; Kaya, A.Y. Impact of Urban Surfaces on Microclimatic Conditions and Thermal Comfort in Burdur, Türkiye. *Atmosphere* **2024**, *15*, 1375. [\[CrossRef\]](#)
18. Martin-Vide, J.; Sarricolea, P.; Moreno-Garcia, M.C. On the definition of urban heat island intensity: The “rural” reference. *Front. Earth Sci.* **2015**, *3*, 24. [\[CrossRef\]](#)
19. Chen, X.-L.; Zhao, H.-M.; Li, P.-X.; Yin, Z.-Y. Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sens. Environ.* **2006**, *104*, 133–146. [\[CrossRef\]](#)
20. Jamei, Y.; Rajagopalan, P.; Sun, Q.C. Spatial structure of surface urban heat island and its relationship with vegetation and built-up areas in Melbourne, Australia. *Sci. Total Environ.* **2019**, *659*, 1335–1351. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Jiang, H.; Guo, H.; Sun, Z.; Xing, Q.; Zhang, H.; Ma, Y.; Li, S. Projections of urban built-up area expansion and urbanization sustainability in China’s cities through 2030. *J. Clean. Prod.* **2022**, *367*, 133086. [\[CrossRef\]](#)
22. Ali, M.I.; Hasim, A.H.; Abidin, M.R. Monitoring the Built-up Area Transformation Using Urban Index and Normalized Difference Built-up Index Analysis. *Int. J. Eng.* **2019**, *32*, 647–653. [\[CrossRef\]](#)
23. Karanam, D.H.K. Study of normalized difference built-up (NDBI) index in automatically mapping urban areas from Landsat TM imagery. *Int. J. Eng. Sci. Math.* **2018**, *7*, 39–48.
24. Zheng, Y.; Tang, L.; Wang, H. An improved approach for monitoring urban built-up areas by combining NPP-VIIRS nighttime light, NDVI, NDWI, and NDBI. *J. Clean. Prod.* **2021**, *328*, 129488. [\[CrossRef\]](#)
25. Alademomi, A.S.; Okolie, C.J.; Daramola, O.E.; Akinnusi, S.A.; Adediran, E.; Olanrewaju, H.O.; Alabi, A.O.; Salami, T.J.; Odumosu, J. The interrelationship between LST, NDVI, NDBI, and land cover change in a section of Lagos metropolis, Nigeria. *Appl. Geomat.* **2022**, *14*, 299–314. [\[CrossRef\]](#)
26. Zhou, M.; He, Y.; Qiu, Z. Construction of a Multi-level Blue-Green Infrastructure Network in a Riverside City: A Case Study of Shaoxing. *Ecosyst. Health Sustain.* **2025**, *11*, 0287. [\[CrossRef\]](#)
27. Lin, Q.; Song, Y.; Zhang, Y.; Hao, J.L.; Wu, Z. Strategies for Restoring and Managing Ecological Corridors of Freshwater Ecosystem. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15921. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Gregory, A.; Spence, E.; Beier, P.; Garding, E. Toward Best Management Practices for Ecological Corridors. *Land* **2021**, *10*, 140. [\[CrossRef\]](#)
29. Kabisch, N.; Selsam, P.; Kirsten, T.; Lausch, A.; Bumberger, J. A multi-sensor and multi-temporal remote sensing approach to detect land cover change dynamics in heterogeneous urban landscapes. *Ecol. Indic.* **2019**, *99*, 273–282. [\[CrossRef\]](#)
30. Singh, P.; Verma, P.; Chaudhuri, A.S.; Singh, V.K.; Rai, P.K. Evaluating the relationship between Urban Heat Island and temporal change in land use, NDVI and NDBI: A case study of Bhopal city, India. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 3061–3072. [\[CrossRef\]](#)
31. Jiang, Y.; Huang, J.; Shi, T.; Wang, H. Interaction of Urban Rivers and Green Space Morphology to Mitigate the Urban Heat Island Effect: Case-Based Comparative Analysis. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11404. [\[CrossRef\]](#) [\[PubMed\]](#)

32. Qin, L.; Liu, H.; Shang, G.; Yang, H.; Yan, H. Thermal Environment Effects of Built-Up Land Expansion in Shijiazhuang. *Land* **2022**, *11*, 968. [[CrossRef](#)]
33. Lu, M.; Fan, H.; Yuan, L.; Li, S.; Wang, H.; Cao, Y.; Liuyang, X. Urban Riparian Green Corridors as Climate-Adaptive Infrastructure: Quantifying Ecological Thresholds for Cooling Performance and Sustainable Management. *Buildings* **2026**, *16*, 660. [[CrossRef](#)]
34. Salici, A.; Hepcan, Ç.C.; Canpolat, E.; Yüksel, A.T. Assessing the cooling effect of the blue corridors in Antakya pre-earthquake, Türkiye. *Urban Clim.* **2025**, *64*, 102610. [[CrossRef](#)]
35. Moisa, M.B.; Dejene, I.N.; Roba, Z.R.; Gemed, D.O. Impact of urban land use and land cover change on urban heat island and urban thermal comfort level: A case study of Addis Ababa City, Ethiopia. *Environ. Monit. Assess.* **2022**, *194*, 736. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.