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EXPANSION OF IMPERVIOUS SURFACES AND THERMO-HYGROMETRIC VARIABILITY IN NORTHERN GOIÂNIA (1985–2020)

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Abstract: *Urbanization alters land cover, the hydrological balance, and local climatic conditions, especially in environmentally strategic areas. This study analyzed the evolution of impervious surfaces in northern Goiânia and discussed their relationship with the temporal variability of annual mean air temperature and relative humidity from 1985 to 2020. The study area was delineated in a GIS environment based on official vector data. Land cover dynamics were analyzed using Landsat imagery processed in Google Earth Engine and classified through a supervised approach. Climatic trends were assessed using the Mann–Kendall test and linear regression. The results indicated an increasing trend in annual mean air temperature and a decreasing trend in relative humidity over the historical series, with a moderate fit for temperature (R^2 = 0.5778) and a lower fit for relative humidity (R^2 = 0.2484). Impervious area showed an overall increasing trend when the 5-year moving average was considered (R^2 = 0.7226). Nevertheless, linear correlations between impervious area and climatic variables were weak, indicating that the observed thermo-hygrometric variability cannot be explained exclusively by soil imperviousness. It is concluded that northern Goiânia underwent a process of territorial transformation consistent with urban expansion, accompanied by local warming and reduced relative humidity, in interaction with regional climate forcings. The results highlight the importance of urban planning oriented toward climate adaptation and the preservation of the environmental functionality of this portion of the municipality.*

Keywords*:* *Urban climatology; climate change; remote sensing; impervious soil; impervious surfaces.*

EXPANSÃO DE SUPERFÍCIES IMPERMEÁVEIS E VARIABILIDADE TERMO-HIGROMÉTRICA NA REGIÃO NORTE DE GOIÂNIA (1985–2020)

Resumo A urbanização altera a cobertura do solo, o balanço hídrico e as condições climáticas locais, especialmente em áreas ambientalmente estratégicas. Este estudo analisou a evolução das superfícies impermeáveis na região norte de Goiânia e discutiu sua relação com a variabilidade temporal da temperatura média anual do ar e da umidade relativa entre 1985 e 2020. A área de estudo foi delimitada em ambiente SIG com base em dados vetoriais oficiais. A dinâmica da cobertura do solo foi analisada por meio de imagens Landsat processadas no Google Earth Engine e classificadas por abordagem supervisionada. As tendências climáticas foram avaliadas utilizando o teste de Mann–Kendall e regressão linear. Os resultados indicaram tendência de aumento da temperatura média anual do ar e tendência de redução da umidade relativa ao longo da série histórica, com ajuste moderado para a temperatura (R^2 = 0,5778) e menor ajuste para a umidade relativa (R^2 = 0,2484). A área impermeável apresentou tendência geral de crescimento quando considerada a média móvel de 5 anos (R^2 = 0,7226). Entretanto, as correlações lineares entre área impermeável e variáveis climáticas foram fracas, indicando que a variabilidade termo-higrométrica observada não pode ser explicada exclusivamente pela impermeabilização do solo. Conclui-se que a região norte de Goiânia passou por um processo de transformação territorial compatível com a expansão urbana, acompanhado por

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aquecimento local e redução da umidade relativa, em interação com forçantes climáticas regionais. Os resultados destacam a importância do planejamento urbano orientado à adaptação climática e à preservação da funcionalidade ambiental dessa porção do município.
Palavras-chave: *Climatologia urbana; mudanças climáticas; sensoriamento remoto; solo impermeabilizado; superfícies impermeáveis.*

1 Introduction

Urbanization is one of the main drivers of environmental transformation in metropolitan areas, promoting changes in land cover, the water balance, and local climatic conditions. In Goiânia, Goiás, Brazil, this process is particularly relevant in the northern portion of the municipality, an area historically associated with the maintenance of important hydrological functions, especially in the dynamics of the João Leite stream and other watercourses that are strategic for the city's water supply and environmental regulation (Assunção, 2012).

In recent decades, population growth and urban expansion have intensified the occupation of this portion of the territory, favoring the progressive replacement of vegetated and permeable surfaces with urbanized areas, exposed soil, and impervious surfaces. This process accompanies Goiânia's demographic expansion and metropolitan consolidation, altering the spatial organization of the city and increasing pressure on environmentally sensitive areas.

From a conceptual standpoint, it is important to distinguish between land cover and land use, since the former refers to the physical covering of the Earth's surface, whereas the latter concerns the way this surface is appropriated and used by human activities. Within the scope of this study, the focus is on the evolution of land cover, with emphasis on urbanized and impervious surfaces, understood as the spatial expression of the urbanization process.

In urban climatology, the city is not understood merely as the physical support for human occupation, but as an active element in the production of a specific climate. In the formulation of the Urban Climate System, Monteiro (1976) interprets urban climate as the result of the interaction between the attributes of urbanization and the atmosphere, while Sant'Anna Neto (2001) highlights the need to understand climate from a geographical perspective, articulating atmospheric rhythms, the production of space, and social processes. In this context, changes in land cover, especially those related to the increase in impervious surfaces and the reduction of vegetation, tend to interfere with the surface energy and water balance, influencing thermal and hygrometric behavior at the local scale.

The literature has shown that urbanization may favor the warming of the urban environment, mainly through increased heat storage, reduced evapotranspiration, and changes in surface roughness. Amorim *et al.* (2009) emphasize that the intensity and spatial extent of urban heat islands depend not only on building density and urban materials, but also on atmospheric conditions, urban morphology, and land use and occupation. At the same time, recent studies have reinforced that the expansion of impervious surfaces constitutes one of the most consistent indicators of urbanization and its environmental effects, due to its association with increased surface runoff, environmental quality degradation, and the intensification of the urban thermal environment (Zhang *et al.*, 2021; Zhao *et al.*, 2023). In Goiânia, Nascimento and Barros (2009) identified expressive thermal differences between urban and rural areas, while Nascimento and Oliveira (2012) demonstrated the temporal evolution of the urban heat island phenomenon in the municipality between 1986 and 2010.

At the same time, the interpretation of local climatic changes cannot disregard the influence of regional controls. Hofmann *et al.* (2021) demonstrated that the Brazilian Cerrado is becoming hotter and drier. More recently, Soares *et al.* (2025), when analyzing municipalities distributed across the biome between 1961 and 2021, identified a trend of increasing air temperature in 13 of the 14 localities evaluated and a reduction in precipitation in a significant portion of the sample, reinforcing evidence of regional climate change in the Cerrado. Thus, trends of increasing temperature and decreasing relative humidity observed at the local scale may reflect the superposition of urbanization processes and background climate changes at the regional scale.

In addition to thermal effects, the expansion of impervious surfaces significantly alters the urban hydrological cycle. In Goiânia, Luiz and Romão (2019) demonstrated that soil imperviousness, associated with rainfall intensity and local physiographic characteristics, favors increased surface runoff and the occurrence of flooding and inundation. Therefore, the discussion of soil imperviousness in northern Goiânia must be understood from an integrated perspective, simultaneously involving urban climate, hydrological dynamics, and territorial planning.

In this scenario, satellite remote sensing constitutes a strategic tool for the multitemporal monitoring of land cover transformations, making it possible to identify spatial patterns of urbanization in long historical series. Recent studies show that the spatiotemporal analysis of impervious surfaces using Landsat time series has been widely employed to characterize urban expansion, its spatial patterns, and its environmental effects, including the application of trend tests and urban growth metrics (Zhao *et al.*, 2023; Xu *et al.*, 2018). Combined with surface meteorological data, this approach makes it possible to investigate how territorial dynamics relate to local climatic trends, although such relationships must be interpreted with caution and from a multiscale perspective.

Therefore, this study aims to analyze the evolution of land cover, with emphasis on the expansion of urbanized and impervious surfaces in northern Goiânia, and to discuss its relationship with the temporal variability of annual mean air temperature and relative humidity.

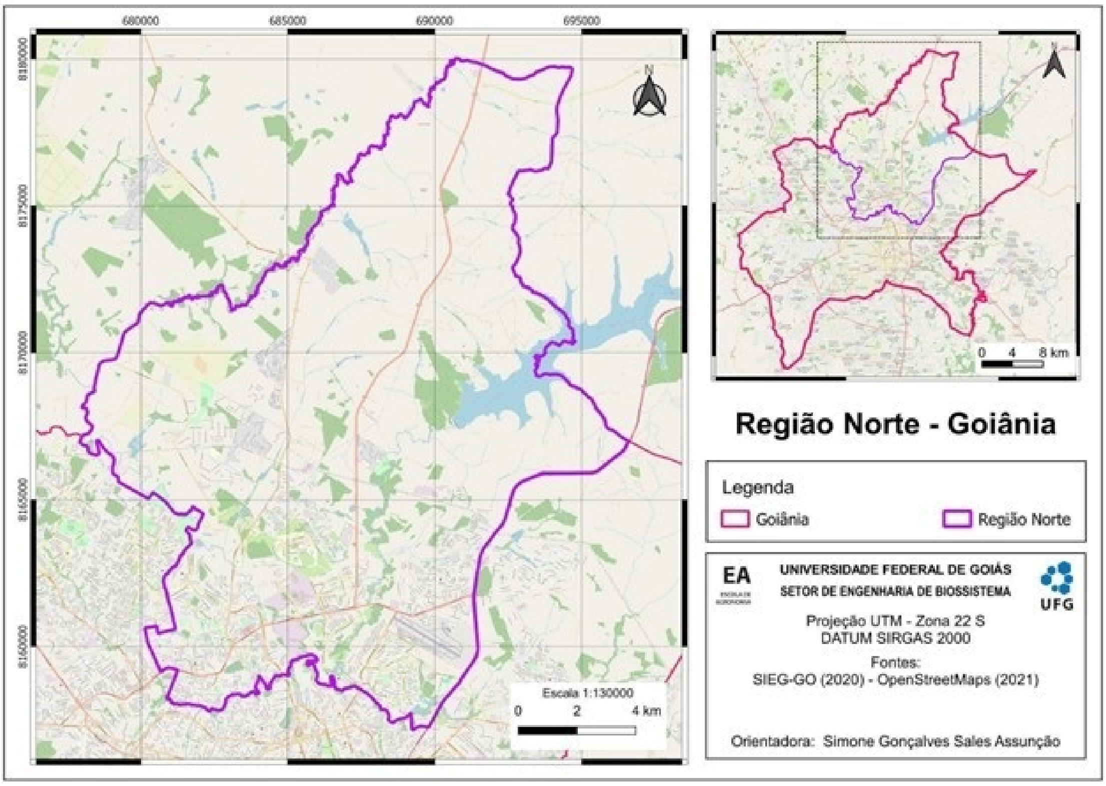
2 Materials and methods

2.1 Study Area

The study area comprises the northern region of the municipality of Goiânia, delimited by Santa Genoveva Airport, the Samambaia Campus of the Federal University of Goiás, and the local Wastewater Treatment Plant. The area includes important water bodies, such as the Meia Ponte River, the Samambaia stream, and the João Leite stream, the latter widely recognized for its importance to the capital’s water supply.

The spatial delimitation was carried out using vector data of neighborhood boundaries made available by the Goiânia City Hall (2021) and municipal boundaries obtained from the State Geoinformation System of Goiás (Governo do Estado de Goiás, 2021). The data were processed in QGIS, where the neighborhoods belonging to the northern region were selected and integrated with adjacent non-urbanized areas, forming a continuous polygon representative of the study area. The final delimitation is presented in Figure 1.

Figure 1. Delimitation of the study area using QGIS software.



Source: The Authors, 2026.

2.2 Meteorological Data

Meteorological data were obtained from the agrometeorological station of the School of Agronomy of the Federal University of Goiás, located within the study area. Daily historical series of air temperature and relative humidity from 1985 to 2021 were used. However, as the 2021 data are incomplete, the annual trend and correlation analyses were performed using only the complete years between 1985 and 2020.

The decision to end the analytical series in 2020 resulted from the need to work only with complete years, ensuring temporal comparability among the annual means of air temperature, relative humidity, and impervious area. Although partial records were available for later periods, their inclusion could introduce bias into the trend analysis, especially because these variables have strong seasonality. Thus, the 1985–2020 time frame was maintained because it comprises a continuous historical series that is sufficiently long for the assessment of climatic and environmental trends, in line with the use of multi-decadal series in climatological studies.

The daily data were aggregated into annual means, generating continuous time series for trend analysis and association with land cover dynamics.

The use of a single source of meteorological data is justified by the location of the agrometeorological station of the School of Agronomy of the Federal University of Goiás within the study area, as well as by the availability of a long and continuous historical series for the period analyzed. This choice made it possible to preserve the homogeneity of the data source over time, an important aspect for trend analyses. Nevertheless, it is acknowledged that the use of a single station limits the representation of intra-urban spatial variability; therefore, the results should be interpreted as indicators of local thermo-hygrometric variability associated with the monitored area, and not as a comprehensive representation of the entire urban climatic field of Goiânia.

2.3 Remote Sensing Data

Land cover analyses were carried out using orbital images obtained through Google Earth Engine (Gorelick *et al.*, 2017). Landsat series images with a spatial resolution of 30 m were used, allowing the construction of a consistent annual time series for the study period.

For each year, a composite image was generated using the median of the available pixels, with the aim of reducing atmospheric effects, noise, and cloud-cover interference.

The reliability of the Landsat series is associated with the temporal continuity of the program, the spatial resolution compatible with multitemporal urban analyses, and the availability of products processed in a standardized manner in a cloud-computing environment. The use of annual median composites contributed to reducing atmospheric interference, radiometric noise, and cloud contamination, favoring the acquisition of representative images for each year analyzed. In addition, the adoption of Google Earth Engine made it possible to apply image selection, composition, and classification procedures uniformly throughout the entire historical series.

2.4 Land Cover Classification

Image classification was performed using a supervised approach. Four thematic classes were defined: impervious area, exposed soil, vegetation, and water bodies.

The training samples were obtained through visual interpretation of high-resolution images in order to ensure the spectral representativeness of the mapped classes. The supervised classification was based on the principles of spectral discrimination of natural targets (Meneses and Madeira Netto, 2001) and on consolidated machine learning methods, with reference to the algorithms discussed by Breiman *et al.* (1984) and Cortes and Vapnik (1995).

As a reliability control procedure, the classification was assessed through the visual coherence of the mapped classes in relation to the reference images and the temporal consistency of the observed spatial patterns. In remote sensing studies of land cover classification, reliability can be measured using validators such as the confusion matrix, overall accuracy, producer's accuracy, user's accuracy, and Kappa index, which are widely used to assess the performance of thematic maps. In the present study, these indicators are considered as a methodological reference for interpreting the results, while acknowledging that the absence of independent sample validation with control points constitutes a limitation to be considered when reading the annual estimates of impervious area.

2.5 Estimation of Impervious Area

The impervious area was estimated by quantifying the pixels classified as impervious surface. For each annual image, the pixels corresponding to the impervious class were counted and converted into total area based on the spatial resolution of the Landsat images. From this estimate, a time series of the expansion of impervious surfaces in northern Goiânia was constructed.

2.6 Statistical Analysis

Trend analysis of the climatic variables was performed using the Mann–Kendall test, which is widely applied to environmental series because it does not require data normality. In addition, simple linear regression models were fitted to estimate the direction of the temporal trend and the coefficient of determination (R^2). The significance of temporal trends was assessed using the Mann–Kendall test, and the magnitude of changes was estimated using Sen's slope.

The relationships between impervious area, annual mean air temperature, and relative humidity were also evaluated using simple linear regression, allowing the magnitude of the associations between the variables to be examined.

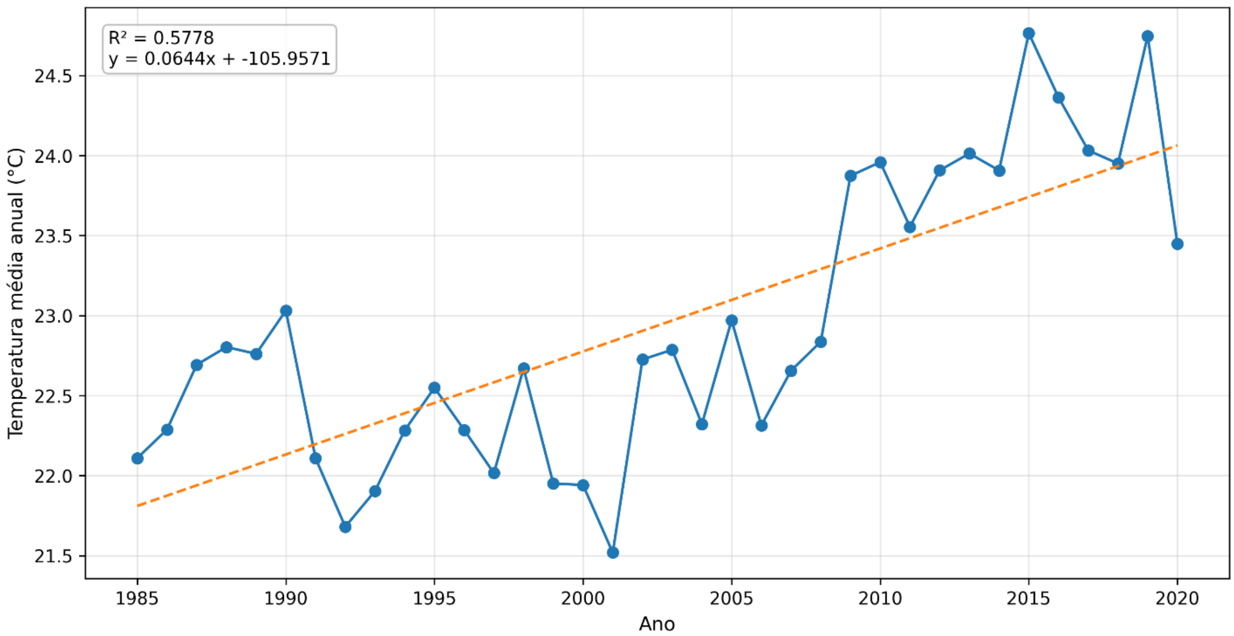
3 Results and Discussion

3.1 Temporal Trends in Annual Mean Air Temperature and Relative Humidity

The analysis of the historical series from 1985 to 2020 revealed an increasing trend in annual mean air temperature and a decreasing trend in relative humidity in northern Goiânia. The non-parametric Mann–Kendall test indicated a statistically significant increasing trend for annual mean air temperature ($S = 328$; $Z = 4.454$; $p < 0.001$) and a significant decreasing trend for relative humidity ($S = -190$; $Z = -2.574$; $p = 0.010$). Sen's slope estimated rates of change of +0.0646 °C per year for temperature and -0.2307 percentage point per year for relative humidity, corresponding, over the analyzed period, to an estimated variation of approximately +2.26 °C and -8.07 percentage points, respectively.

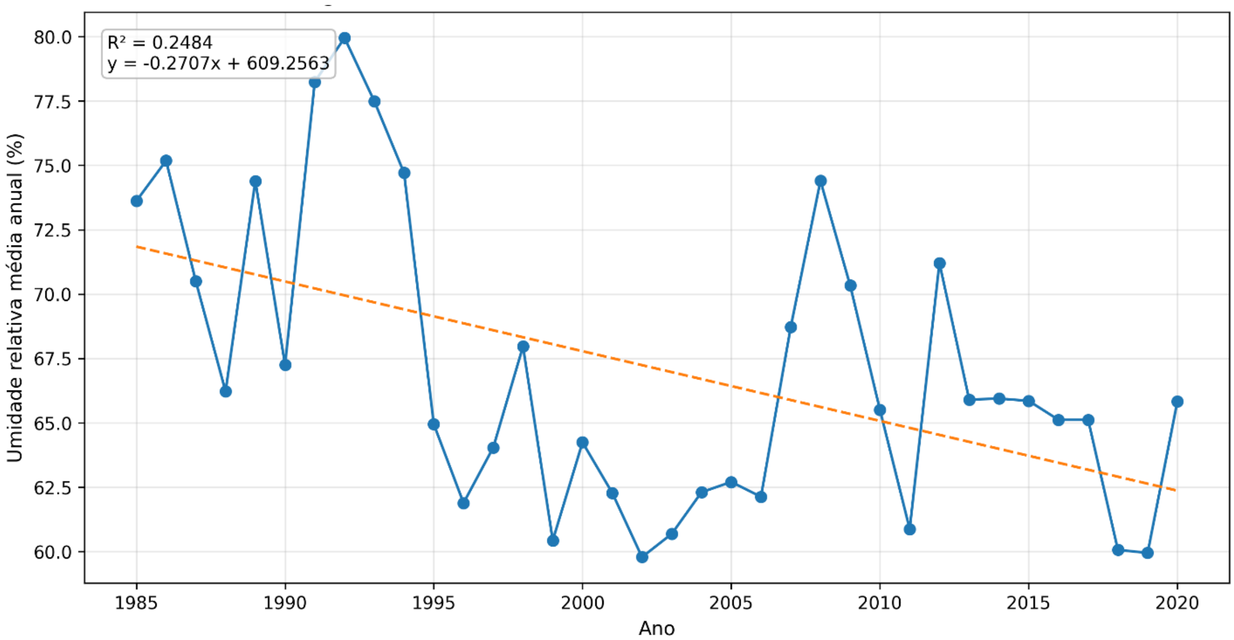
Complementarily, linear regression showed a moderate fit for temperature ($R^2 = 0.5778$) and a lower fit for relative humidity ($R^2 = 0.2484$), indicating that the temporal trend is more consistent for the thermal variable than for the hygrometric variable. The temporal evolution of annual mean air temperature is presented in Figure 2, in which a gradual increase in the variable can be observed throughout the series, with warming intensifying in recent decades. Figure 3 shows the variation in annual mean relative humidity, evidencing a general decreasing trend, although with greater interannual variability.

Figure 2. Temporal evolution of annual mean air temperature in northern Goiânia between 1985 and 2020, with linear trend line and coefficient of determination.



Source: The Authors, 2026.

Figure 3. Temporal evolution of annual mean relative humidity in northern Goiânia between 1985 and 2020, with linear trend line and coefficient of determination.



Source: The Authors, 2026.

This behavior is compatible with the urban climatology literature. In the formulation of the Urban Climate System, Monteiro (1976) understands urban climate as the product of interactions between urbanization and the atmosphere, highlighting the thermodynamic subsystem as a central component in the generation of thermal anomalies. From a complementary perspective, Sant’Anna Neto (2001) emphasizes that the geographical analysis of climate must incorporate the social production of space and atmospheric rhythms, reinforcing the need to interpret the results of this study in light of the territorial transformations that have occurred in northern Goiânia.

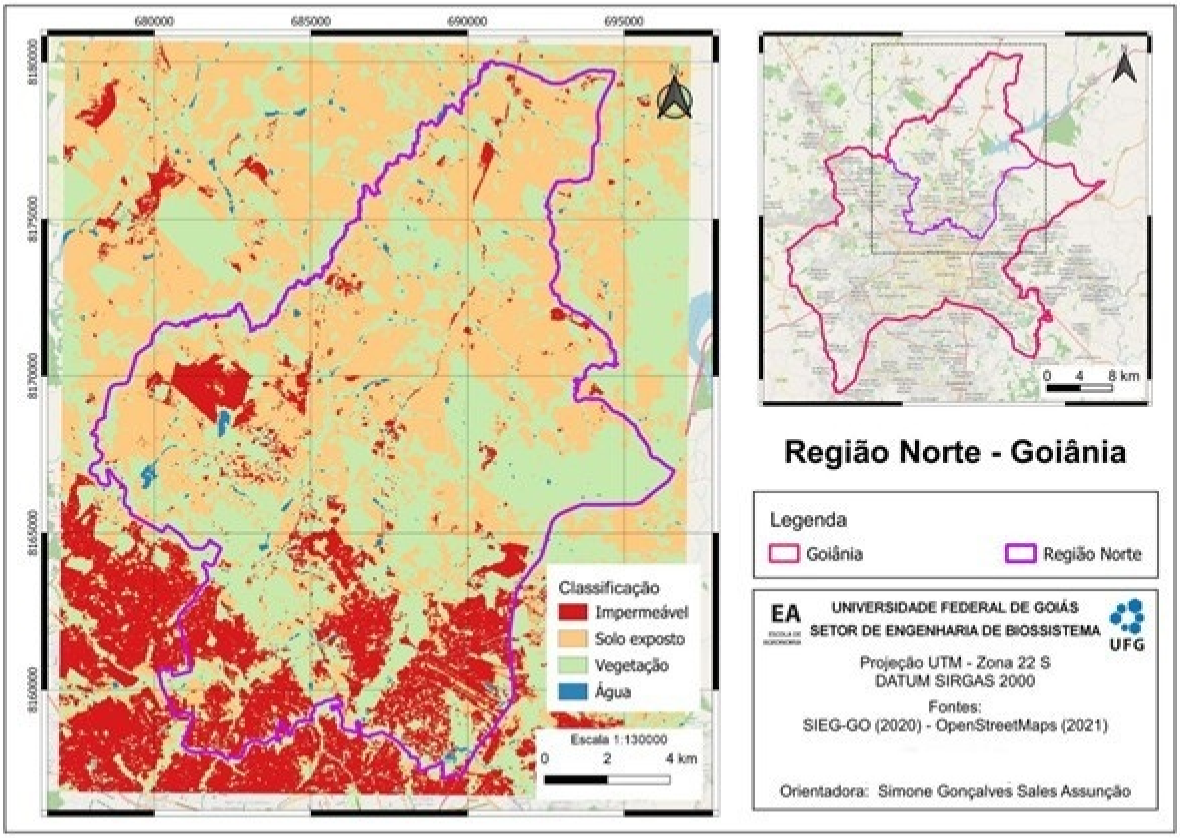
In the case of Goiânia, the results are consistent with previous investigations that identified important changes in the urban thermal field. Nascimento and Barros (2009), using remote sensing, recorded differences of up to 10 °C between urban and rural areas, associating higher temperatures with certain anthropogenic land uses and more urbanized sectors. Nascimento and Oliveira (2012), in turn, demonstrated the evolution of the heat island phenomenon in the municipality between 1986 and 2010, with an expansion of the domain of higher surface temperature classes over time. Thus, the results presented here reinforce the interpretation that local urban dynamics have been accompanied by changes in the city's thermal behavior.

However, the interpretation of these results requires caution. Although there is convergence between increasing temperature and the growth of imperviousness, the linear regressions between impervious area and climatic variables showed low explanatory power, especially in the case of relative humidity. This result is consistent with the literature showing that the expansion of impervious surfaces is more directly associated with the surface thermal environment and the intensification of urban heat than, necessarily, with air temperature in simple annual series, since the atmospheric response also depends on synoptic controls, the scale of observation, and landscape configuration (Yang *et al.*, 2019; Li *et al.*, 2018). In addition, relative humidity responds strongly to thermal behavior and to the influence of atmospheric processes at the regional scale. In this sense, Hofmann *et al.* (2021) demonstrated a trend toward warming and drying in the Brazilian Cerrado, suggesting that part of the signal observed in Goiânia may result both from local land-use changes and from a broader regional climatic context.

3.2 Soil Imperviousness and Land Cover Dynamics

The spatial distribution of land cover classes for the year 2007 is presented in Figure 4. In this classification, impervious areas corresponded to 10.91% of the mapped surface, while vegetation represented 72.91%, exposed soil 16.07%, and water bodies 0.10%. Despite the predominance of vegetation cover, the presence of impervious areas and extensive exposed soil surfaces already reveals a landscape undergoing transformation, consistent with the advance of urbanization in the study area.

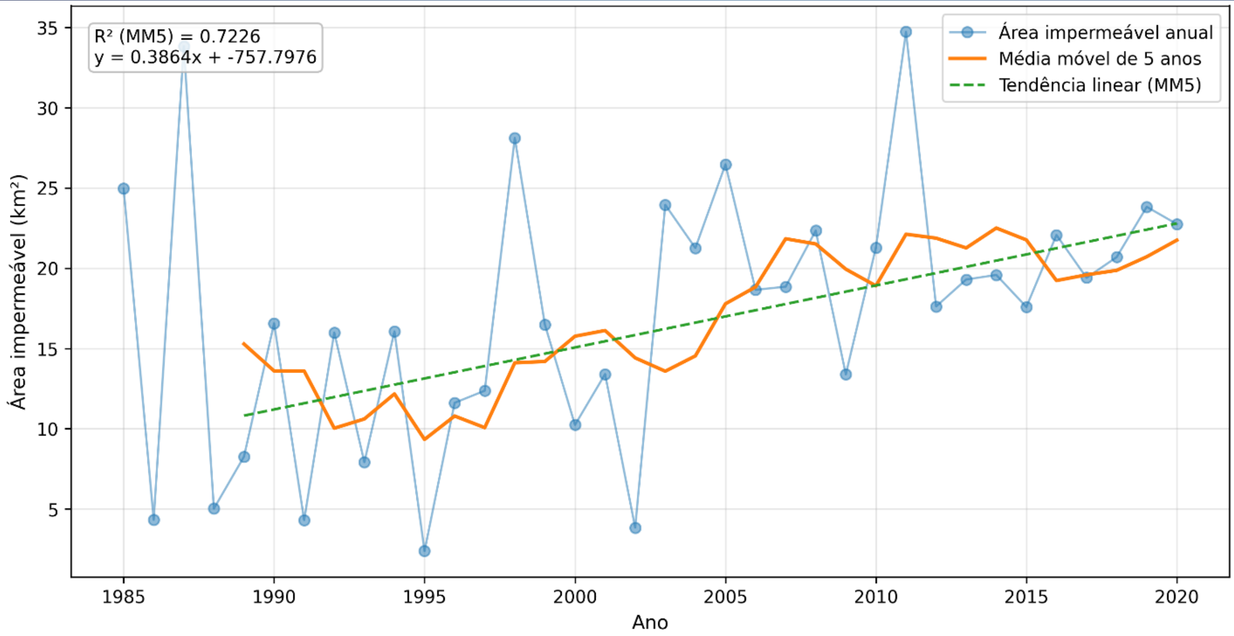
Figure 4. Land cover classification in northern Goiânia in 2007.



Source: The Authors, 2026.

The temporal evolution of impervious area is presented in Figure 5, which shows the annual series and the 5-year moving average. The annual series showed marked interannual variation, with minimum values of 2.37 km² in 1995 and maximum values of 34.74 km² in 2011, while in 2020 the estimated impervious area was 22.75 km². The Mann–Kendall test indicated a statistically significant increasing trend for impervious area ($S = 208$; $Z = 2.820$; $p = 0.0048$), and Sen's slope estimated an expansion rate of +0.3755 km² per year. When analyzed using the 5-year moving average, the growth trend becomes even more evident, with a linear fit of $R^2 = 0.7226$, indicating a progressive increase in surface imperviousness in the study area.

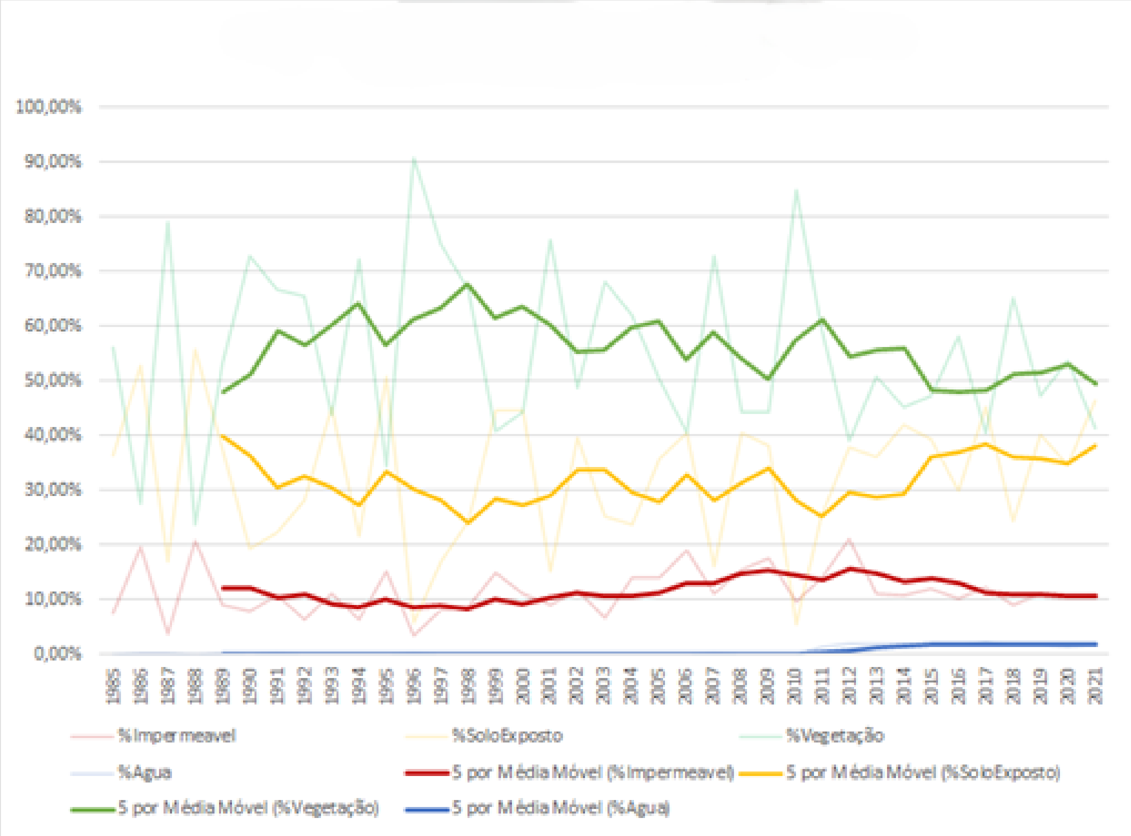
Figure 5. Evolution of impervious area in northern Goiânia between 1985 and 2020, with 5-year moving average and linear trend.



Source: The Authors, 2026.

Figure 6 shows the percentage evolution of land cover classes throughout the historical series, evidencing a landscape in transition. Vegetation remained the dominant class, but was accompanied by fluctuations and relative growth of impervious surfaces and exposed soil.

Figure 6. Percentage evolution of land cover classes in northern Goiânia throughout the historical series.



Source: The Authors, 2026.

Taken together, Figures 4, 5, and 6 indicate that northern Goiânia underwent gradual changes in its spatial configuration, with an increase in urbanized surfaces and a reorganization of the other land cover classes.

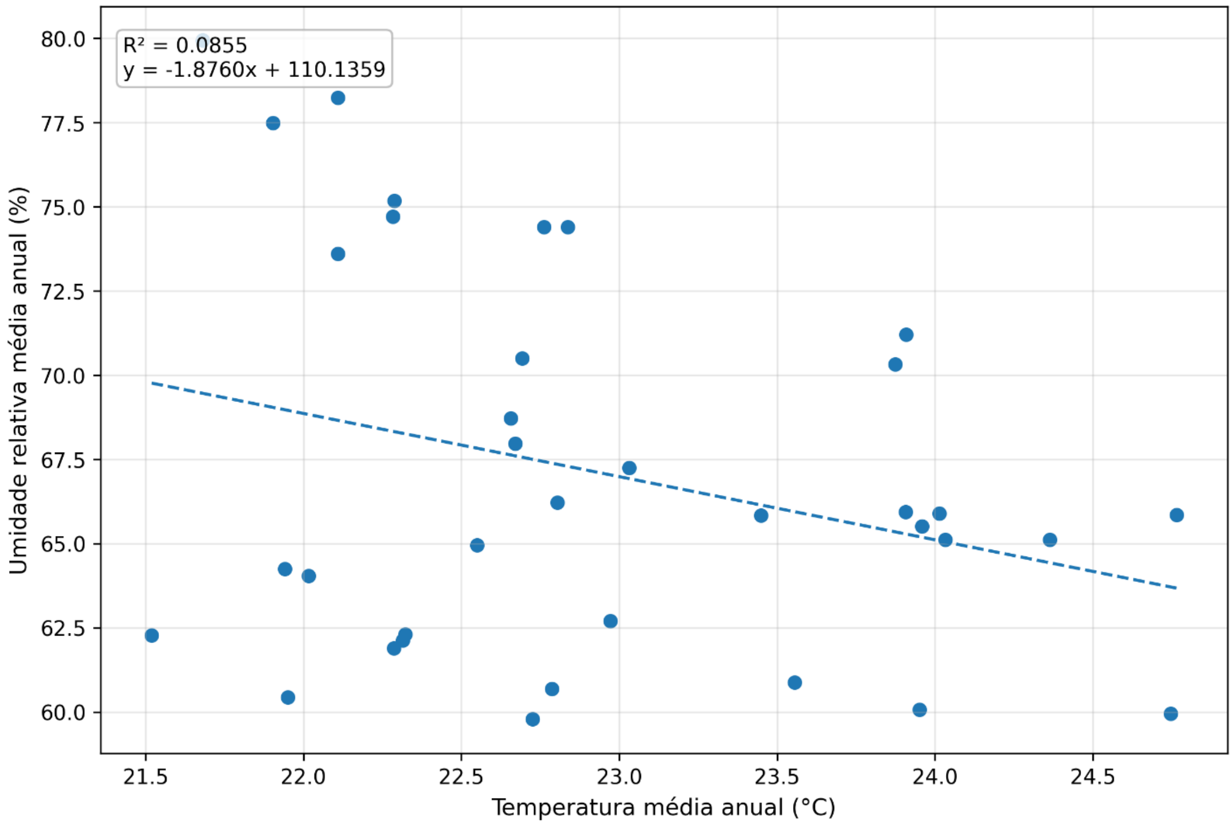
From an environmental standpoint, the increase in imperviousness implies the replacement of surfaces with greater infiltration and evapotranspiration potential by urban materials that store heat, reduce infiltration, and alter the surface water and energy balance. This interpretation is consistent with Luiz and Romão (2019), who demonstrated that the expansion of impervious surfaces in Goiânia directly interferes with the processes of the urban hydrological cycle, increasing surface runoff and reducing infiltration efficiency.

The methodological consistency of the multitemporal mapping also deserves emphasis. The use of Landsat images processed in Google Earth Engine proved adequate for analyzing the spatiotemporal dynamics of land cover, especially due to the possibility of accessing extensive historical series and standardized processing (Gorelick *et al.*, 2017). This choice is in line with recent studies that use Landsat series to monitor the evolution of impervious surfaces at multitemporal scales, highlighting the usefulness of this type of data for investigating urban growth, expansion patterns, and associated eco-environmental effects (Xu *et al.*, 2018; Zhang *et al.*, 2021; Zhao *et al.*, 2023). In addition, the supervised classification adopted in this study is aligned with the foundations of remote sensing and machine learning, relying both on the spectral discrimination of natural and anthropogenic targets (Meneses and Madeira Netto, 2001) and on classical classification algorithms (Breiman *et al.*, 1984; Cortes and Vapnik, 1995).

3.3 Relationships Between Climatic Variables and Imperviousness

Figure 7 presents the scatter plot between annual mean air temperature and relative humidity, evidencing an inversely proportional relationship between the variables. This behavior is physically expected, since warmer years tend to present lower relative humidity values.

Figure 7. Scatter plot between annual mean air temperature and annual mean relative humidity in northern Goiânia between 1985 and 2020.

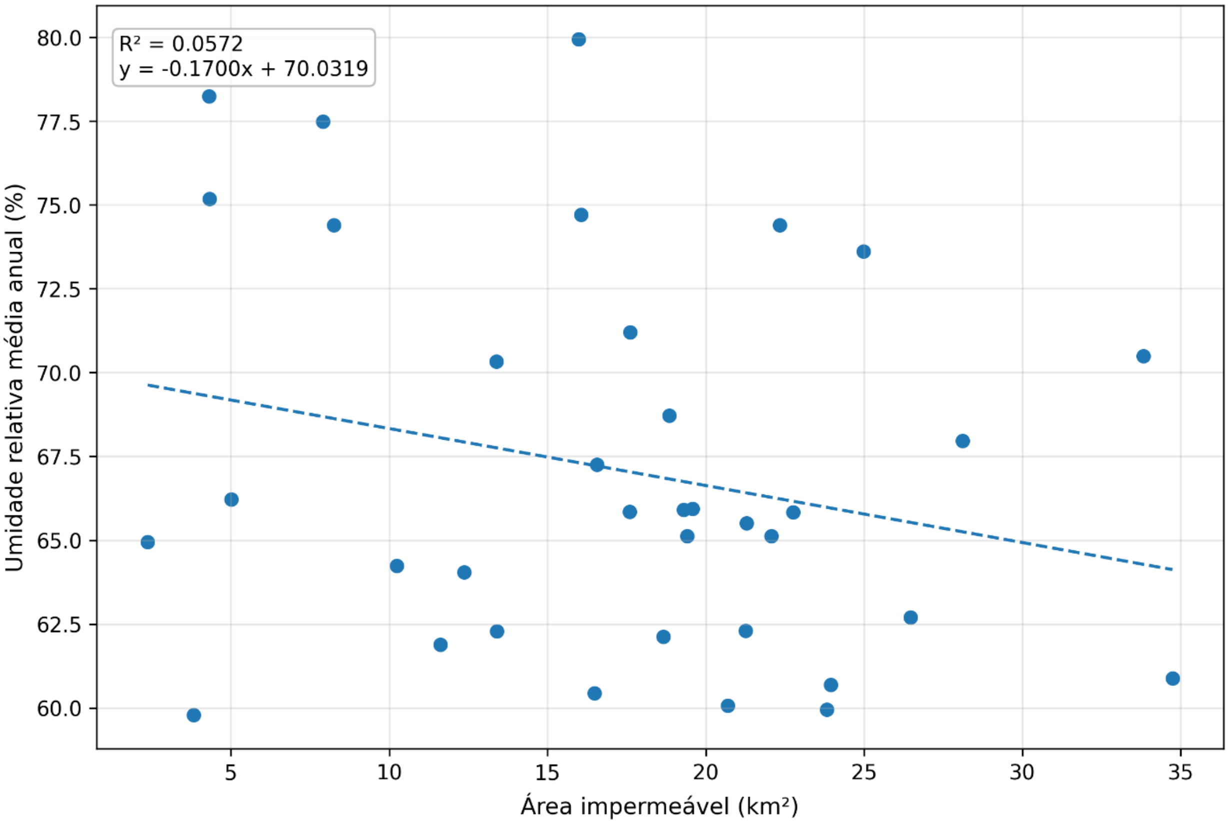


Source: The Authors, 2026.

Regarding the relationship between impervious area and relative humidity, Figure 8 shows a low-magnitude linear association, with $R^2 = 0.0572$.

Figure 8. Scatter plot between impervious area and annual mean relative humidity in northern Goiânia between 1985

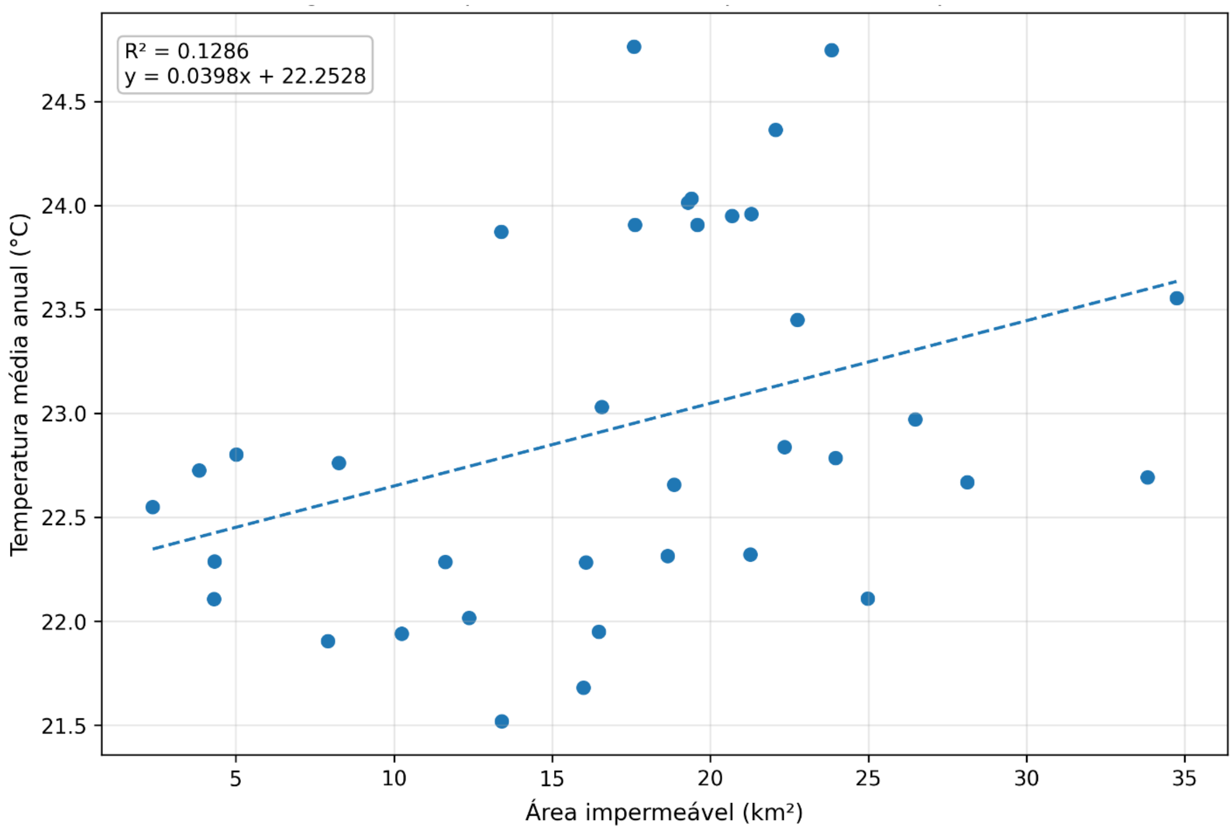
and 2020.



Source: The Authors, 2026.

Similarly, Figure 9 presents the relationship between impervious area and annual mean air temperature, with $R^2 = 0.1286$, also indicating low explanatory power of the simple linear model.

Figure 9. Scatter plot between impervious area and annual mean air temperature in northern Goiânia between 1985 and 2020.



Source: The Authors, 2026.

These results show that the expansion of impervious surfaces is consistent with the urban transformation of the study area, but does not, in isolation, explain the thermo-hygrometric variability observed throughout the period. This point is central to the interpretative robustness of the study. In its classical conception, the urban heat island does not simply correspond to the absolute increase in temperature in an urbanized area, but rather to the thermal contrast between urban areas and less densely built-up areas. Amorim *et al.* (2009) emphasize that its intensity depends on urban morphology, construction materials, atmospheric conditions, and the succession of weather types. Nascimento and Barros (2009) also highlight that the phenomenon is influenced not only by land cover, but also by geoecological factors and the regional meteorological system.

Thus, the low R^2 values do not invalidate the relevance of imperviousness as a component of the urbanization process, but indicate that the local climatic response is modulated by multiple factors. In the case of temperature, the low-magnitude positive association suggests that the expansion of impervious surfaces participates in the process of local warming, but does not determine it in isolation. In the case of relative humidity, the even weaker association reinforces that this variable is particularly sensitive to atmospheric controls operating at scales broader than the intra-urban scale.

3.4 Environmental and Urban Planning Implications

The results obtained have relevant implications for urban and environmental planning. The expansion of impervious surfaces, associated with the warming trend and the reduction in relative humidity, suggests a process of territorial transformation that simultaneously affects thermal comfort, hydrological dynamics, and the ecological functionality of the study area.

In the context of northern Goiânia, this aspect is even more sensitive, since this portion of the city has historically been important for the municipality's hydrological and environmental regulation. Assunção (2012) had already highlighted the importance of assessing environmental risks in urban areas of the Metropolitan Region of Goiânia based on the articulation between natural processes and forms of land occupation. In the same direction, Luiz and Romão (2019) demonstrate that imperviousness, combined with the intensity of rainfall events and local physiographic characteristics, favors increased surface runoff and the occurrence of flooding and inundation.

From the perspective of climate adaptation, the results reinforce the need for urban planning strategies that preserve and expand vegetated areas, promote water infiltration into the soil, and reduce the spatial continuity of impervious surfaces. This recommendation converges with studies that point to the expansion of impervious surfaces as a central component of urban environmental degradation, with implications for surface runoff, warming, and ecosystem deterioration, reinforcing the need for territorial planning that is more attentive to the spatial structure of urbanization (Zhang *et al.*, 2021; Zhao *et al.*, 2023).

These actions directly relate to the Sustainable Development Goals, especially SDG 11, aimed at promoting sustainable cities and communities, and SDG 13, related to action against global climate change (ONU, 2015). In this sense, the results of this study not only describe environmental trends, but also provide support for territorial planning and for the formulation of more resilient and integrated urban policies.

3.5 Critical Analysis

Taken together, the results show that northern Goiânia underwent a process of territorial transformation consistent with urban expansion, accompanied by an increasing trend in annual mean temperature, a reduction in relative humidity, and growth in impervious area. The interpretation of these results is consistent with the urban climatology literature and with studies previously conducted in Goiânia and in the Cerrado.

However, the weak correlations between impervious area and climatic variables indicate that such changes should not be attributed exclusively to soil imperviousness. The most robust interpretation, therefore, is one that recognizes the combined influence of local surface alteration processes and regional climatic forcings, avoiding reductionist explanations and strengthening the analytical solidity of the manuscript.

In addition, the results align with recent literature that treats impervious surface as a key indicator of urbanization and its environmental effects, while also indicating that the relationship between urbanization and climate should be interpreted from a multiscale perspective, articulating local surface transformation with broader climatic trends in the Cerrado (Soares *et al.*, 2025; Zhang *et al.*, 2021).

4 Conclusion

The results of this study demonstrated that the northern region of Goiânia underwent a process of territorial transformation consistent with urban expansion throughout the analyzed period, evidenced by the growth of impervious surfaces and the reorganization of land cover classes. In parallel, the meteorological series indicated an increasing trend in annual mean temperature and a reduction in relative humidity, signaling consistent changes in local thermo-hygrometric conditions. Sen’s slope estimated rates of change of +0.0646 °C per year for annual mean temperature and -0.2307 percentage point per year for relative humidity, corresponding, over the analyzed interval, to an estimated variation of approximately +2.26 °C and -8.07 percentage points, respectively.

The integrated analysis of remote sensing and meteorological data made it possible to identify that the expansion of imperviousness accompanies the urbanization process in the study area and constitutes a relevant element for understanding the observed environmental changes. However, the low coefficients of determination obtained in the correlations between impervious area and climatic variables indicate that the variability of temperature and, especially, relative humidity cannot be explained exclusively by soil imperviousness. Thus, the most consistent interpretation is one that recognizes the simultaneous influence of local surface alteration processes and regional climatic forcings.

From a methodological standpoint, the use of Landsat images processed in Google Earth Engine and the application of supervised classification proved adequate for the multitemporal analysis of the spatial dynamics of land cover, making it possible to monitor the evolution of urbanization over an extensive historical series. The use of the Mann–Kendall test, Sen’s slope, and linear regression also contributed to providing greater robustness to the trend analysis, meeting the need for more consistent statistical treatment of the data.

In applied terms, the results reinforce the importance of northern Goiânia in the context of urban and environmental planning, especially due to its relevance to the municipality's hydrological and ecological dynamics. Thus, strategies aimed at preserving vegetation cover, expanding permeable areas, controlling disorderly urban expansion, and incorporating nature-based solutions may simultaneously contribute to mitigating local warming, improving microclimatic conditions, and reducing the hydrological impacts associated with urbanization.

Finally, future studies are recommended to advance the comparison between urban and non-urbanized areas, incorporate complementary climatic variables, and use orbital thermal data and more detailed intra-urban measurements in order to deepen the understanding of the relationships between urbanization, imperviousness, and local climate in Goiânia.

5 References

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