RESEARCH PAPER

URBAN TRANSFORMATION IN LAHORE: THREE DECADES OF LAND COVER CHANGES, GREEN SPACE DECLINE, AND SUSTAINABLE DEVELOPMENT CHALLENGES

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ABSTRACT. Pakistan has experienced significant urbanization, characterized by rapid urban population growth and unplanned urban expansion, making it the most urbanized country in South Asia. This study focuses on Lahore, the second-largest megacity of Pakistan, and evaluates land cover changes over the last three decades (1990-2020). It also analyzes the relationship between urban green landscapes and unregulated urban expansion. The study reveals significant changes in the ecology of Lahore's urban landscape using Landsat imagery, including Landsat 5 TM, Landsat 8 OLI, and a 30m spatial resolution, along with population data from the Pakistan Bureau of Statistics. In particular, the study reveals a decline in urban green spaces and a significant expansion of urban built-up areas in Lahore. The annual urban area expansion rates were 24.2 km^2 (1990-2000), 12.1 km^2 (2000-2010), and 26.4 km^2 (2010-2020), while vegetation cover decreased 33.45 km^2 (1990-2000), 20 km^2 (2000-2010) in the first two decades but slightly increased from 2010 to 2020 at an annual rate of 14.17 km^2. As a result, there is a serious concern about the rapid decline of green space in Lahore. It is recommended that the administrative authorities follow the World Health Organization's guidelines regarding the need for green spaces. This study contributes to achieving the United Nations' Sustainable Development Goal 11th, indicator 11.3.1, and provides guidelines for conserving natural, social, and economic resources in the face of rapid urbanization.

KEYWORDS: land cover changes, green spaces, sustainable development, SDG 11, Lahore

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INTRODUCTION

The expansion of urban areas over time has led to the depletion of natural resources and environmental degradation, particularly green spaces, as shown by studies investigating land use and land cover changes (Puplampu and Boafo 2021). Ongoing urban growth in Pakistan's megacities, especially in Lahore, raises significant environmental and sustainability issues (Nasar-u-Minallah et al. 2021; Nasar-u-Minallah et al. 2023). The reduction of green spaces due to land overdevelopment, population growth, and industrial expansion has disrupted the delicate balance of ecosystems (Jabbar et al. 2024). Therefore, monitoring and preserving tree cover in urban areas is increasingly important for environmental conservation (Semeraro et al. 2021; Hanif et al. 2022; Fatima et al. 2023). Urban green spaces (UGS) are open areas in urban and semi-urban regions that are free to the public and characterized by substantial vegetation cover. These spaces include trees in parks, forests, roadways, farms, and environmental conservation areas. They are widely recognized for their ability to mitigate the adverse effects of urbanization on land use (Semeraro et al. 2021). Establishing and improving urban green spaces can serve as suitable infrastructure options to enhance the quality of life and promote the sustainability and security of biodiversity systems, energy, health, water, food, and flood mitigation (Zia et al. 2022). UGS play a crucial role in reducing the impact of urban heat islands and enhancing urban water management (Mukherjee et al. 2018; Nasar-u-Minallah 2018; Nasar-u-Minallah 2019; Nasar-u-Minallah and Ghaffar 2020). The development of urban green spaces is a fundamental goal in creating livable cities, as the quantity and distribution of UGS significantly influence a city's long-term sustainability (Jabbar et al. 2024). The overall number of green spaces in a particular area indicates a high-quality life and a healthy ecosystem (Alam et al. 2014). The development of UGS is crucial for creating livable cities, as their quantity and distribution are key to the sustainability of the city (Brown et al. 2010).

According to (United Nations 2018) projections, the global urban population will increase by 70% by 2050, leading to the expansion of metropolitan areas and an increase in natural resource consumption, which will negatively impact human health (Semeraro et al. 2021). As a large city, Lahore has been the subject of numerous studies examining urban and ecological issues (Bhalli and Ghaffar 2015; Nasar-u-Minallah 2023). Spatial and temporal analysis of land change in cities like Lahore can provide valuable insights for administrative authorities. The present research focuses on Lahore to better understand the distribution and provision of green spaces for a sustainable ecosystem. Consequently, it is essential to develop urbanization models, approaches, and programs that enhance the quality of life in urban areas while minimizing their local and global impacts (Semeraro et al. 2021). A comprehensive understanding of this phenomenon and its patterns can inform the effective utilization of urban green spaces. Despite the many studies on land use changes in Lahore, the evaluation of city agglomeration types and the relationship between green space and population growth using landscape metrics remain unexplored in the existing literature. An advanced platform, known as Google Earth Engine, enables the categorization and processing of multi-resolution and multi-temporal satellite images for specific sites, facilitating geospatial analysis (Lin et al. 2021). This web-based tool, freely accessible for academic research, has proven useful in examining urban landscape changes (Sidhu et al. 2018). Furthermore, the availability of Landsat satellite data since 1972, accessible online, allows for the analysis of surface patterns, contributing to outcomes with accuracy rates of at least 75% (Dwyer et al. 2018; Tsai et al. 2018; Zia et al. 2022; Sahar et al. 2023; Zia et al. 2023; Mazhar et al. 2024).

Urban green spaces play a crucial role in mitigating the adverse effects of rapid urban expansion by providing numerous environmental, social, and economic benefits (Jabbar et al. 2024). These spaces, including parks, gardens, and forests, act as vital lungs for cities, filtering air pollutants and mitigating the urban heat island effect (Alam et al. 2014; Garcia et al. 2019). They also enhance biodiversity, offering habitats for various species amidst urbanization. Moreover, urban green spaces contribute to the well-being of urban residents by providing opportunities for recreation, exercise, and social interaction, thus improving physical and mental health outcomes (Bratman et al. 2012). However, as cities expand, there is a growing concern over the loss of green spaces due to infrastructure development and urban sprawl, necessitating proactive planning strategies to preserve and expand these essential urban ecosystems (Fletcher et al. 2019).

Green spaces are increasingly recognized as vital components of urban areas, offering a multitude of benefits essential for city well-being and sustainability. Recent research emphasizes their crucial role in mitigating the impacts of climate change, particularly in reducing urban heat island effects and improving air quality (Schiopu & Teodosiu 2021; Nasar-u-Minallah 2019). These spaces also act as carbon sinks, sequestering carbon dioxide and other pollutants while simultaneously providing shade and cooling effects through evapotranspiration, enhancing urban resilience to rising temperatures (Shen et al. 2022). Furthermore, urban green spaces contribute significantly to public health by promoting physical activity, mental well-being, and social cohesion (Gascon et al. 2022). They offer opportunities for recreation, relaxation, and social interaction, which are increasingly valued in densely populated urban environments. Additionally, green spaces support urban biodiversity, provide habitats for diverse flora and fauna, and play a critical role in ecosystem services such as pollination and water filtration (Elmqvist et al. 2020). Therefore, the preservation and expansion of green spaces in urban areas are paramount for creating sustainable and livable cities that prioritize environmental quality and human health.

Urban expansion poses significant threats to green spaces, jeopardizing their ecological integrity and the numerous benefits they provide to urban communities. Recent studies highlight the escalating pressures on green spaces due to infrastructure development, population growth, and land-use changes (Bhalli and Ghaffar 2015; Minallah et al. 2016a; Minallah et al. 2016b; Bhalli et al. 2013) associated with urbanization (Soga et al. 2022; Bhalli et al. 2012a). These threats include habitat loss, fragmentation, and degradation, leading to declines in biodiversity and ecosystem services (Zhang et al. 2021). Additionally, urban expansion often results in the conversion of green spaces into impervious surfaces, exacerbating issues such as flooding and heat stress while reducing infiltration capacity and water quality (Chen et al. 2022; Zia et al. 2016b). Furthermore, the loss of green spaces diminishes opportunities for recreation, social interaction, and mental well-being among urban residents, exacerbating inequalities in access to nature (Grimm et al. 2021). Therefore, effective urban planning strategies that prioritize the conservation and sustainable management of green spaces are essential for mitigating the adverse impacts of urban expansion and ensuring the resilience and livability of cities.

The rapid expansion of urban areas poses a significant threat to green spaces, which provide ecological integrity and multilevel benefits to the environment and human well-being. As cities continue to grow at extraordinary rates, green spaces face increasing pressures from land-use changes. These threats result in habitat loss, fragmentation, and degradation, leading to declines in biodiversity and ecosystem services. Furthermore, the conversion of green spaces into impervious surfaces exacerbates issues such as urban heat island effects, flooding (Zia et al. 2021c), and water pollution, while also diminishing opportunities for recreation, social interaction, and mental health benefits among urban residents. Thus, understanding the complexities and impacts of rapid urban expansion on green spaces is essential for informing effective conservation strategies and urban planning initiatives aimed at preserving these vital urban ecosystems. The rapid growth of cities puts green spaces in danger. These areas, like parks and forests, are important for both nature and people. But as cities grow larger, more land is being utilized for buildings and roads, causing a reduction in green spaces. Animals and plants lose their homes, and communities lose the benefits such spaces bring, such as cleaner air and places to relax. When green spaces disappear, problems such as floods and pollution often become worse. Additionally, there are fewer places to enjoy nature or meet with friends outdoors. As such, it is crucial to understand how the rapid growth of cities can affect green spaces. By studying these patterns, green spaces can be protected sustainably. This study aims to deepen the understanding of Lahore's green space, distribution, and sustainability to provide useful knowledge for policymakers and urban planners.

MATERIAL AND METHODS

Study Area

Lahore, the second-largest megacity in the Punjab Province of Pakistan, is located on the left bank of the river Ravi (Shirazi et al. 2016), within latitudes 31.20°N to 31.71°N and longitudes 74.00°E to 74.65°E. Its exceptional connectivity with other urban and rural areas in the province, as well as its status as an industrial hub, have propelled its rapid urbanization and development over the past few decades. This rapid urbanization has markedly transformed the natural surface into the urban landscape (Zia et al. 2021a; Nasar-u-Minallah 2020). The population of the Lahore district has seen considerable growth, rising from 6.3 million (6,318,745 individuals) in 1998 to 11.13 million (11,126,285 individuals) in 2017 (GOP 2017). As a centre of culture, education, and business, Lahore plays a pivotal role in the region. The Lahore city district covers an area of 1772 km^2. For administrative purposes, the Lahore city district is divided into five tehsils: Lahore Cantt, Lahore City, Model Town, Raiwind, and Shalimar, further organized into nine zones/towns, as illustrated in Fig. 1.

Lahore is facing significant changes in its urban, social, and environmental landscape. Over recent years, the city has experienced rapid urbanization, with its built-up area nearly doubling between 1999 and 2011. This expansion has strained infrastructure and governance, leading to issues like uncontrolled urban growth and inefficiencies in managing construction (Bhalli et al. 2012b). To cope with this growth, Lahore requires well-organized institutions. Despite improvements in transportation and efforts to restore the walled city, effective population management remains crucial (Rana & Bhatti 2018). The population of the study area has steadily increased since the 1998 Census, resulting in urban sprawl, the loss of green spaces, and damage to natural habitats. This expansion, primarily occurring on agricultural land, poses significant socio-environmental challenges, including overpopulation and environmental degradation (Shirazi & Kazmi 2014).

Despite differences in infrastructure and socioeconomic growth among districts in Punjab province, Lahore remains the most developed. However, local administrations struggle to manage development challenges effectively despite national efforts to reduce these disparities (Rana & Arshad 2017). Environmental issues have significant socio-environmental impacts, particularly the loss of urban greenery and trees. Rapid urbanization in Lahore has led to a considerable decrease in green spaces, affecting the city's appearance and worsening environmental problems (Shirazi & Kazmi 2016). Public opinion polls indicate that population growth and urbanization are the primary drivers of vegetation loss, highlighting the importance of sustainable urban planning and preserving green areas.

Data Acquisition

This study utilized Landsat satellite imagery, with the specifics of the Landsat datasets presented in Table 1. The study used four Landsat images from different sensors, including three from Landsat 5 TM for 1990, 2000, and 2010 and one from Landsat 8 (OLI_TIRS) for 2020. These sensors vary in spectral, spatial, and temporal resolutions. Additionally, data from the Punjab Bureau of Statistics[1] played a crucial role in analyzing various city locations, enabling a comprehensive comparison of urbanization trends and changes in urban green spaces over the past

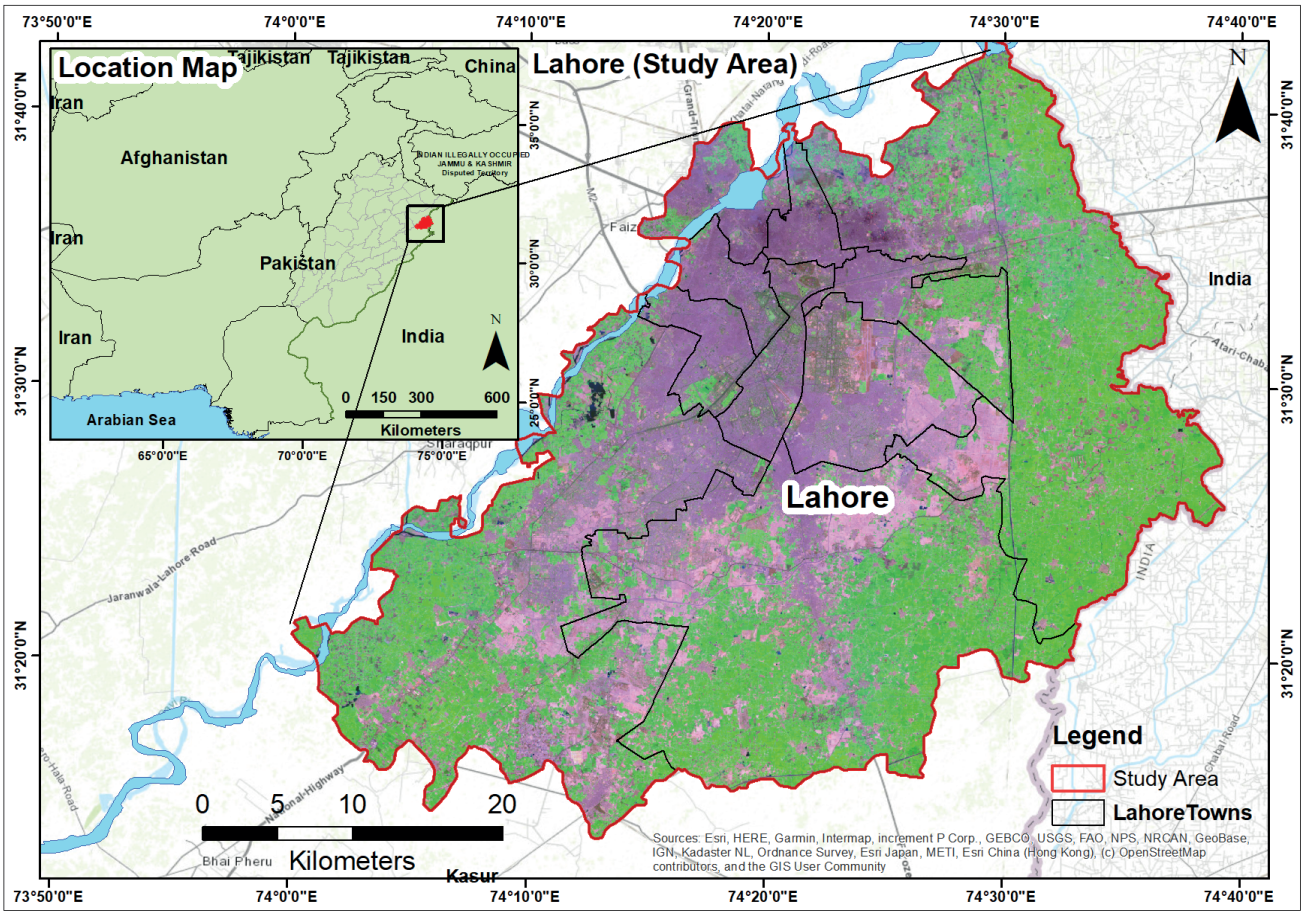

Fig. 1. Location map of the study area District Lahore

[1]Punjab Bureau of Statistics (2015). Punjab Development Statistics 2015. Lahore. Retrieved from http://www.bos.gop.pk/publicationreports

three decades. The Lahore district shape file, obtained from the Punjab Bureau of Statistics, was instrumental in this analysis. Population data were derived from the 1998 census, and projections for 2010 and 2020, based on the 2017 data, were sourced from the Punjab Bureau of Statistics website:

$$P(t) = P_0 ekt \quad (1)$$

where variable t represents time, k represents growth rate, and P_0 represents the initial population.

Data analysis

This study examines the spatial and temporal changes in land use and land cover in Lahore, Pakistan, and their relationship with the loss of Urban Green Spaces (UGS) and population growth. Landsat 5 TM and Landsat 8 OLI satellite imagery with a spatial resolution of 30 meters were employed for this analysis. The Google Earth Engine (GEE) was used to classify images of Lahore for the years 1990, 2000, 2010, and 2020. Additionally, the study applies a formula to evaluate indicator 11.3.1, as described by Nicolau et al. (2018):

$$LCRPGR = (Land\ consumption\ rate\ /\ Population\ growth\ rate) \quad (2)$$

where Land consumption rate= $ln\ (Urb_{t+n}/Urb_t)/n$ and Population growth $rate= ln\ (Pop_{t+n}/Pop_t)/n$

The analysis of spatiotemporal patterns of land use and land cover, along with its correlation with the decline of green spaces and population growth, was conducted in this study. The methodology was divided into three distinct categories, as illustrated in Fig. 2.

This study analyzed spatiotemporal patterns of land use and land cover, and its correlation with the decline of green spaces and population growth. Defined as publicly owned areas accessible without restriction (hereafter referred to as UGS), these spaces include parks, street roundabouts, and medians, which are all characterized by their lack of physical barriers to access. Data for the years 1990, 2000, 2010, and 2020 were acquired during February and March to select cloud-free images, as these months typically have minimal cloud cover. Landscape metrics were used to measure patterns and analyze changes in urban areas over specified periods. Each pixel in the satellite imagery grid represents a digital number corresponding to the captured data. A supervised image classification methodology was applied to categorize the data from the satellite imagery. Various tools for satellite image analysis provide a broad spectrum of capabilities for conducting different types of image classification. In this study, Landsat 5 TM and Landsat 8 OLI satellite images, with a spatial resolution of 30 meters, were processed and classified using Google Earth Engine. Machine learning classifiers, known for their superior accuracy over traditional methods, were used (Tsai et al. 2018).

Table 1. Landsat Datasets Specifications

Year	Satellite	Acquisition date	Accuracy (%)
1990	Landsat 5 TM	09-02-1990	88
2000	Landsat 5 TM	10-02-2000	82
2010	Landsat 5 TM	03-02-2010	92
2020	Landsat 8 (OLI_TIRS)	05-03-2020	86

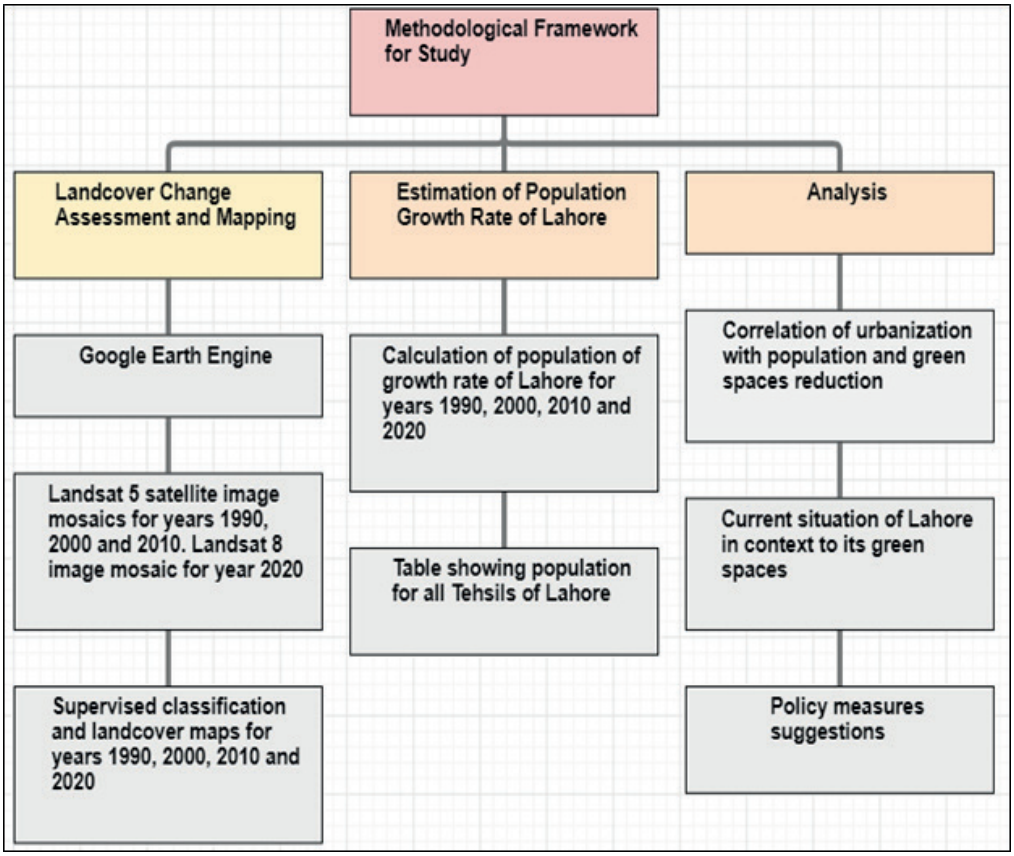

Fig. 2. Methodological framework of study

Table 1 details the satellite images used to classify land cover in the Lahore district for 1990, 2000, 2010, and 2020. Due to their high spatial resolution and advanced capabilities, the chosen satellite imagery and classification approach enhance the accuracy and reliability of the analysis. Machine learning algorithms for image classification require a substantial dataset, particularly more training data points for land cover representation. However, machine learning classifiers have consistently demonstrated greater accuracy than conventional image classification methods. This study utilized the CART algorithm, a binary decision tree method based on "if-then" questions at each node, for image classification. Applying the CART classifier to land cover mapping produced highly favourable outcomes, with accuracies typically exceeding 75%. The analysis identified four distinct land cover categories: vegetation, water bodies, urban areas, and barren areas. As noted by Megahed et al. (2015), the Kappa coefficient is a statistical measure for assessing the level of agreement in validating the obtained results. It ranges from +1, indicating perfect agreement, to -1, indicating complete disagreement, with 0 signifying an agreement level as expected by chance (Paudel & Yuan 2012). In this study, Kappa values were calculated for all classified images, showing promising results of 0.75 (for 1990), 0.71 (for 2000), 0.87 (for 2010), and 0.73 (for 2020). These Kappa coefficients confirm the reliability and robustness of the classification results across all analyzed images.

Estimation of the population of Lahore

The population estimates for the years 1990, 2000, 2010, and 2020 were obtained from available census data. Specifically, the population figures for 1990 and 2000 were calculated using the 1998 census data, while those for 2010 and 2020 were based on the 2017 data provided by the Pakistan Bureau of Statistics[2]. For Lahore Cantt Tehsil, the estimated population growth rate was 5.03% in 1990 and 3.07% in 2000, 2010, and 2020. In Lahore City Tehsil, the projected growth rate was 3.14% for 2000, 2010, and 2020, with a rate of 2.65% for 2000 in the same tehsil. The growth rate for Model Town Tehsil was estimated to be 3.14% for 2000, 2010, and 2020, and 3.48% for 2000. Raiwind Tehsil experienced a growth rate of 3.14% in 2000, 2010, and 2020 and 4.64% in 2000. Lastly, Shalimar Tehsil grew by 3.14% in 2000, 2010, and 2020, with a rate of 2.47% in 2000. Lastly, Shalimar Tehsil had a growth rate of 3.14 % in 2000, 2010, and 2020, with a rate of 2.47 % in 2000. The population growth estimation followed the formula $P(t) = P_0ekt$, where $P(t)$ represents the population at a given time, P_0 is the initial population, t represents time, and k denotes the growth rate. This formula was used to project the population figures for different years, considering the estimated growth rates for each tehsil in Lahore.

RESULTS

Fig. 3(a) depicts the map of land use changes, providing a detailed overview of Lahore's land cover composition in 1990. This illustration visually represents urban land, water bodies, barren land, and vegetation cover, facilitating a clear understanding of Lahore's land dynamics during this specific period and highlighting the initial state of these critical land cover components. Fig. 3(b) delivers an in-depth view of the land cover changes within Lahore's tehsils in 2000, indicating a decrease in vegetation from 1205 km^2 to 870 km^2 and an increase in built-up area from 218 km^2 to 460 km^2. Fig. 3(c) presents a detailed

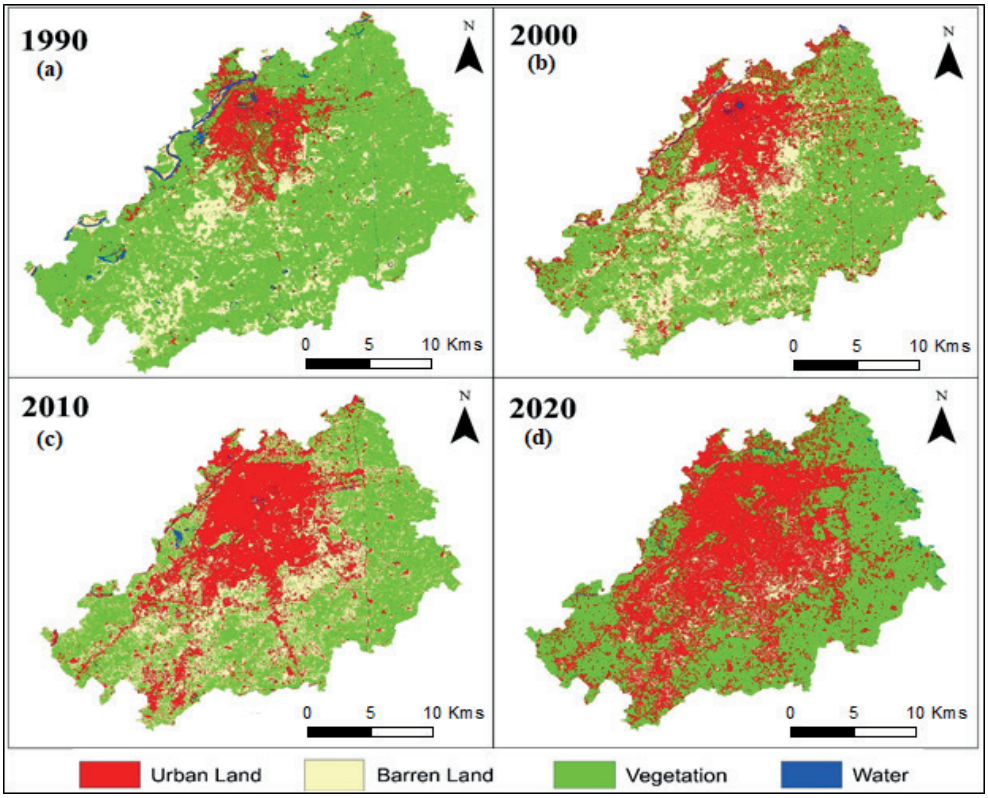

Fig. 3. Land Use/Land Covers of Lahore from 1990 to 2020

[2]Pakistan Bureau of Statistics (1998). Census report of Pakistan 1998. Islamabad. Retrieved from http://www.pbs.gov.pk/population-tables
Pakistan Bureau of Statistics (2017). Provisional summary results of 6th population and housing census 2017. Islamabad. Retrieved from http://www.pbscensus.gov.pk/
Pakistan Bureau of Statistics. Census 1998; 2005. http://www.pbs.gov.pk/
Pakistan Bureau of Statistics. Census 2017; 2018. http://www.pbs.gov.pk/

examination of the land cover of Lahore in 2010, revealing a decrease in vegetation from 870 km^2 to 671 km^2 and an increase in built-up area from 460 km^2 to 582 km^2. Lastly, Fig. 3(d) offers a comprehensive land cover assessment for Lahore's tehsils in 2020, showing an increase in vegetation from 671 km^2 to 812 km^2 and in the built-up area from 582 km^2 to 846 km^2.

Lahore's land use and land cover changes were calculated for all five tehsils (Lahore Cantt, Lahore City, Model Town, Raiwind, and Shalimar), as shown in the figures below. These images collectively provide a decade-by-decade overview of Lahore's land cover evolution from 1990 to 2020. For a specific year, each figure details the areas of urban land, water bodies, barren land, and vegetation cover within Lahore. This series of visuals facilitates a comparative analysis of how land use and environmental dynamics have shifted over time, offering valuable insights into land use trends and land cover change in the city. This study contributes new perspectives on land use and land cover change in Lahore and establishes a correlation between the reduction of green space and the increase in population and urbanization. The findings of this research align well with those of previously published studies, as illustrated in Fig. 4.

Fig. 5 illustrates the average changes in vegetation and urbanization. From 1990 to 2000, vegetation decreased by 33.45 km^2. Between 2000 and 2010, it further decreased by 20 km^2. However, from 2010 to 2020, vegetation increased by 14.17 km^2. This increase in vegetation is attributed to the expansion of housing societies, which typically include open spaces, parks, and areas of vegetation. Government initiatives, such as clean and green projects and the Billion Tree Tsunami project, have also contributed to this increase.

Fig. 6 depicts the land cover characteristics of Lahore's tehsils in 1990, detailing the areas in square kilometers for urban land, water bodies, barren land, and vegetation cover. Fig. 6 presents the land use/land covers of the study area for 2020 at the tehsil level, revealing a significant increase in built-up areas and a decrease in urban green spaces. These study area results indicate that the study area is facing rapid urbanization, which is removing green spaces from the study area. This figure is a valuable tool for understanding the land dynamics within Lahore at the beginning of the study period, providing exact measurements and proportions of these critical land categories in square kilometers.

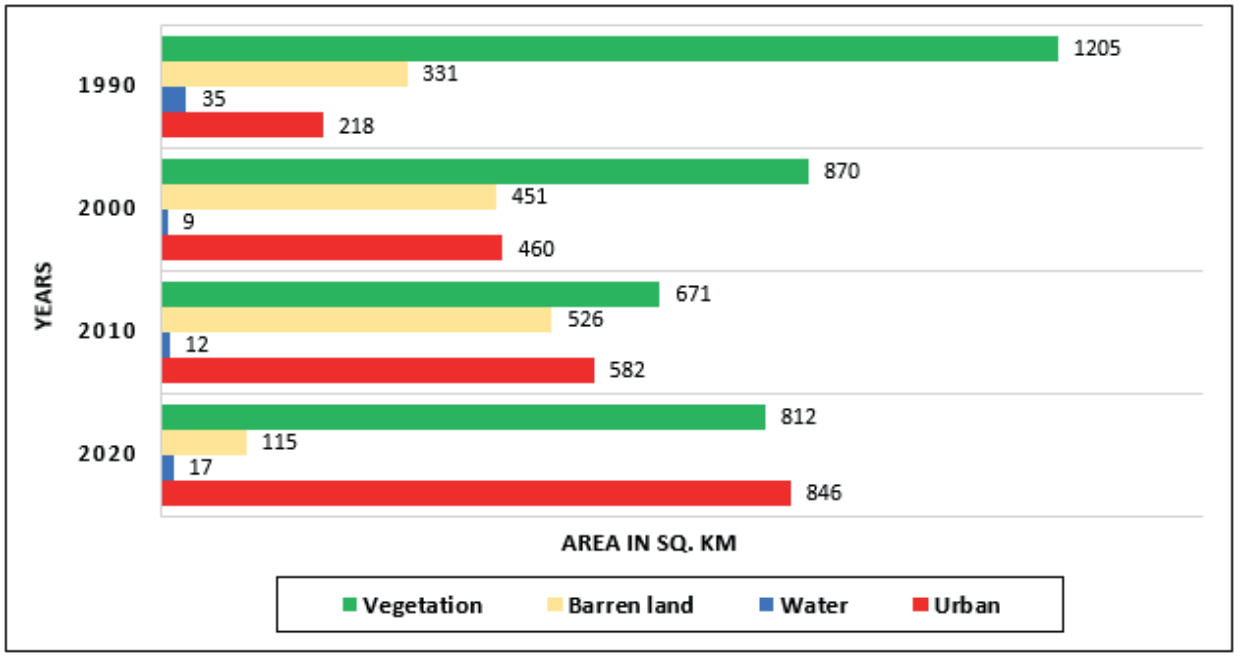

Fig. 4. Temporal statistics of Land cover changes in Lahore

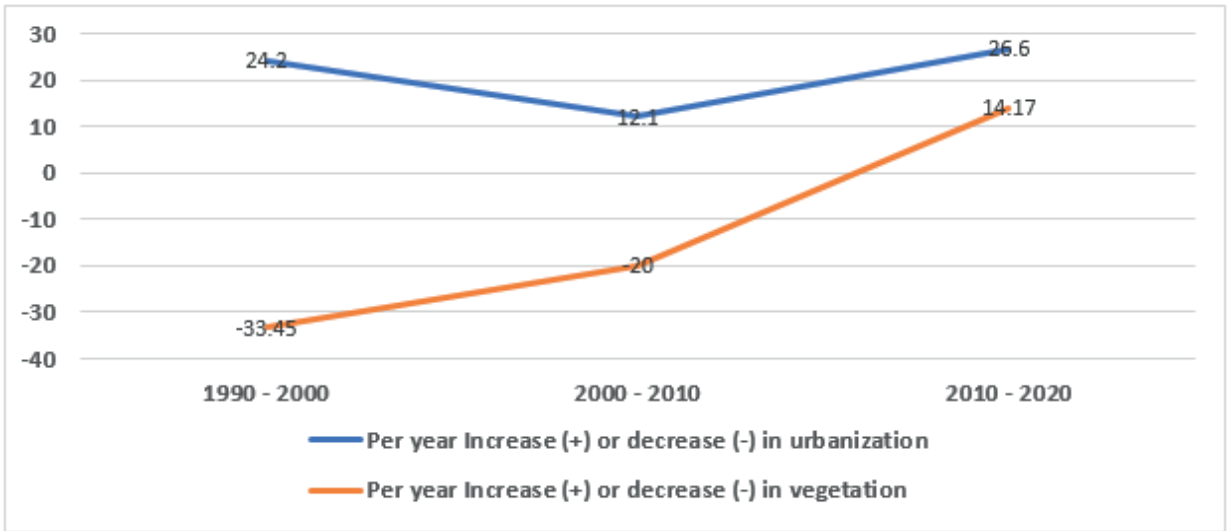

Fig. 5. Increase and decrease in vegetation and urbanization

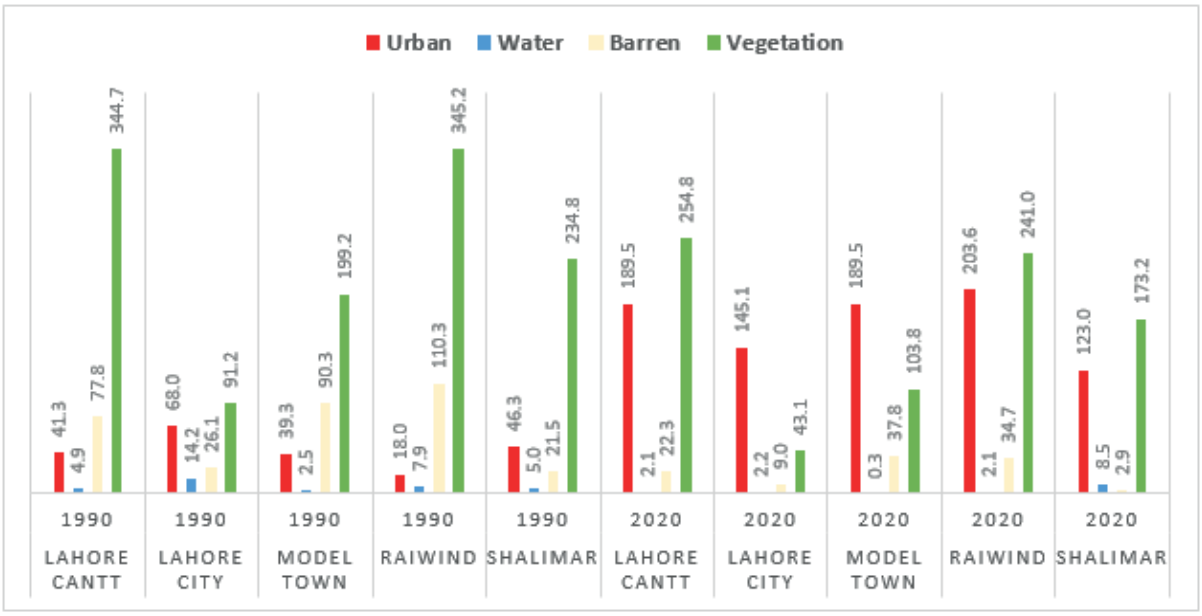

Fig. 6. Land Use/Land Cover changed in Lahore at Tehsil level in 1990 and 2020 in km²

The relationship between population density and Urban Green Spaces (UGS) in Lahore reveals a notable trend, which can be characterized as when population density increases, green spaces diminish. This study analyzed population data to calculate the number of individuals per square kilometer in Lahore, employing population growth rates from the Punjab Bureau of Statistics for various tehsils within the city. The study determined the population and green spaces per person by applying these growth rates for the years 1990, 2000, 2010, and 2020. The results indicate a significant decrease in vegetation across all tehsils of Lahore with increasing population density, illustrating an inverse relationship between population growth and green space availability, as depicted in Fig. 7.

The analysis of land use and land cover changes highlights that urbanization initially centred on the Walled City in 1990 and 2000. However, by 2010 and 2020, areas that were already populated saw further growth, leading to overpopulation, particularly in Shalimar, Cantonment, Gulberg, Samanabad, and Iqbal Town. The expansion of urban areas into these regions is clearly illustrated in the maps for 2010 (Fig. 3(c)) and 2020 (Fig. 3(d)). 1990 Lahore boasted 1205 km² of vegetation, with population density concentrated around the walled city. By 2000, urban land expansion led to a reduction in vegetation to 870.5 km², a trend that continued into 2010, with vegetation further decreasing to 670.8 km² amidst rapid population growth. By 2020, the urban area had expanded to 846.4 km², a significant increase from the 218 km² in 1990. The transformation of barren land into commercial areas and housing societies, often incorporating green spaces like parks and recreational facilities, led to a slight increase in vegetation by 14.17 km² between 2010 and 2020. These findings demonstrate the direct correlation between urbanization, increased population density, and the diminishing availability of green spaces. Fig. 7 provides a comprehensive analysis of the relationship between population density and UGS in Lahore from 1990 to 2020, visually highlighting the inverse correlation between population growth and the preservation of green spaces within the city over the three decades. Fig. 7 also offers a detailed examination of the relationship between population density and urbanization trends in Lahore over the years 1990, 2000, 2010, and 2020. This visual portrayal underscores a pronounced correlation, where population increases are closely linked to expansions in urban built-up areas. It demonstrates that as the population has risen, the extent of the urban built-up area within Lahore has also markedly increased, highlighting the direct connection between demographic changes and urban development in the city. This correlation is critical for understanding urban expansion dynamics and planning for sustainable urban growth, considering the impact on infrastructure, green spaces, and the overall urban ecosystem.

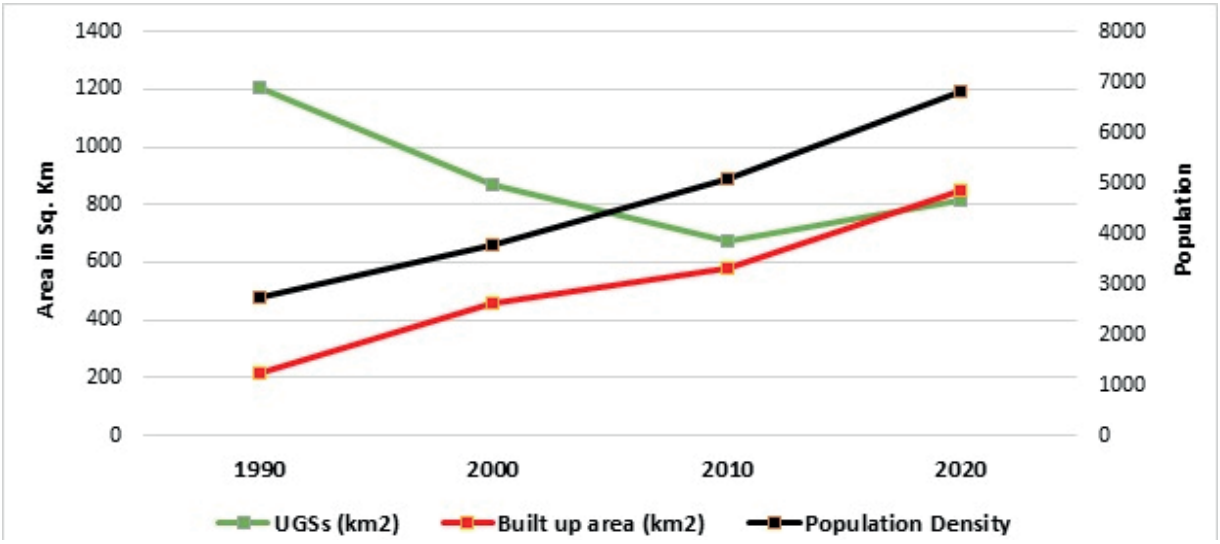

Fig. 7. Correlation between built-up area, UGSs and population density in Lahore

Green Spaces Access to Public

The World Health Organization (WHO) guidelines advocate for a minimum of 9 square meters of green space per person (Alam et al. 2014), serving as a crucial benchmark for designers and city administrators in their planning and remediation efforts (Alam et al. 2014). In Lahore, the 2016-2021 Master Plan proposes a land requirement ratio for open green spaces of 0.50 hectares per 1000 people, equating to 0.0005 hectares or 5 square meters per person. This ratio significantly undercuts the WHO's recommended guideline, highlighting a gap in the city's planning standards.

Furthermore, the Lahore Master Plan also fails to adequately categorize urban green spaces, primarily focusing on recreational spaces such as parks. However, a comprehensive review of the literature demonstrates the necessity of incorporating a variety of green spaces beyond mere recreational areas. Fig. 8 presents a comparative analysis of the urban green spaces available per person within the tehsils of Lahore for the years 1990, 2000, 2010, and 2020, measured in square meters. This analysis provides a detailed examination of the evolution of green space availability per capita over these decades. Most significantly, it displays the changes in urban green spaces concerning population growth, highlighting the effects of urbanization on access to green areas in Lahore.

The findings of this study indicate an abundance of green spaces distributed across all tehsils of Lahore, as shown in Fig. 8. Despite the urban expansion leading to decreased vegetation and a significant decline in green spaces over three decades, the results suggest that Lahore provides sufficient green spaces per person, aligning with the World Health Organization's (WHO) recommendation of a minimum of 9 square meters per person (Alam et al. 2014). However, it is critical to note the potential limitations of these findings due to inaccuracies in data measurement. Additionally, agricultural areas on the outskirts of Lahore were considered green spaces for this analysis, which may influence the overall assessment of urban green space availability.

In this study, overall environmental justice studies are integral to urban management discussions, highlighting the importance of equitable green space distribution among urban populations with important considerations such as ethnicity, culture, and socioeconomic status. These studies examine the spatial allocation of social benefits, including access to green spaces. The results have found that poor neighborhoods often have less access to these essential resources (Xiao et al. 2017; Wu et al. 2021). Since urban parks are a finite natural resource that cannot be provided indefinitely or uniformly across all areas, ensuring equitable access to green spaces is critical in urban planning and management.

Evaluation of SDG 11 Indicator 11.3.1

The evaluation of Sustainable Development Goal (SDG) 11th indicator 11.3.1 involved estimating the surface area occupied by urban areas and the population residing in these areas for each specified year, following the methodology proposed by Nicolau et al. (2018). This assessment aimed to examine the relationship between land consumption and population growth by calculating the land consumption rate (LCR) and population growth rate (PGR) and deriving the ratio of LCR to PGR (LCRPGR).

In Cantt Tehsil and Lahore City Tehsil, the LCRPGR ratio decreased across the periods between the years 1990-2000, 2000-2010, and 2010-2020. This indicates that population growth outpaced land consumption during these periods. Model Town Tehsil saw a decrease in the ratio between 1990-2000 and 2000-2010, suggesting a more substantial population increase than land consumption. However, the ratio increased from 2000-2010 to 2010-2020, reflecting land consumption and population growth. For Raiwind Tehsil, the LCRPGR ratio increased between 1990-2000 and 2000-2010, indicating a higher increase in land consumption relative to population growth. The ratio decreased from 2000-2010 to 2010-2020, indicating that population growth exceeded the land consumption rate during this latter period. In Shalimar Tehsil, a negative

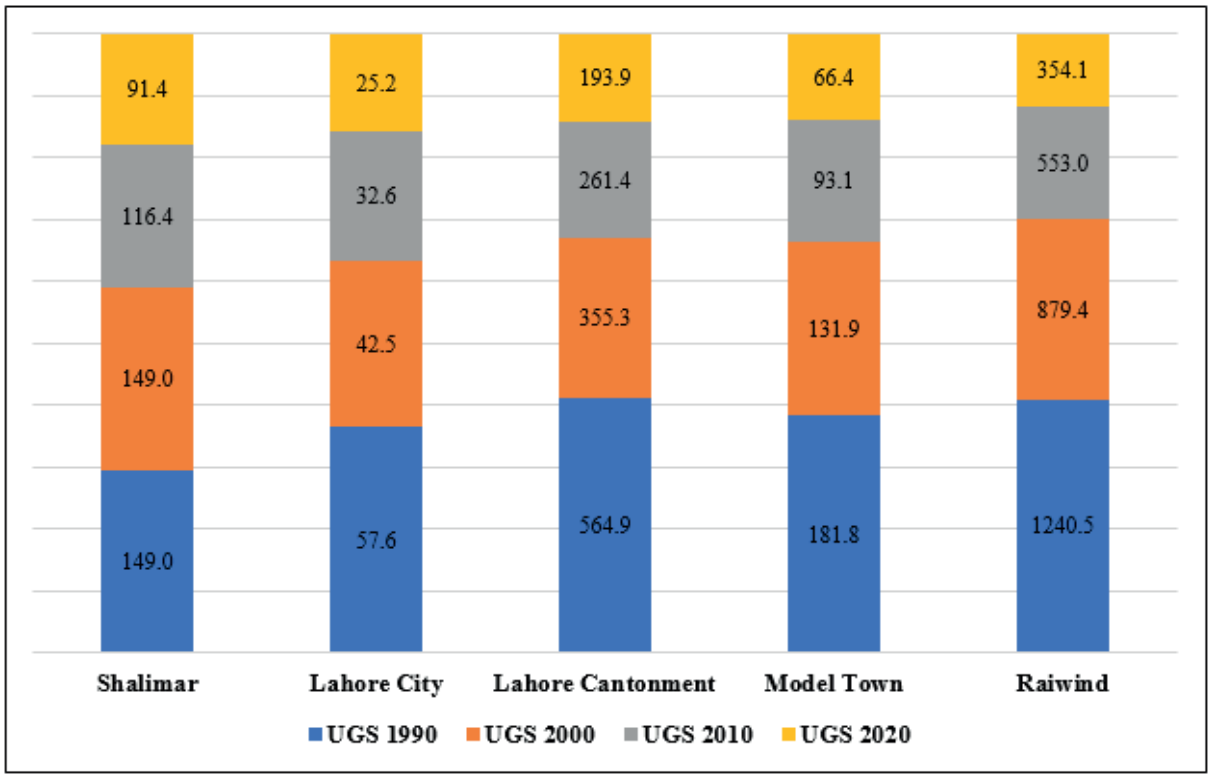

Fig. 8. Urban green spaces per person per meter (1990, 2000, 2010 and 2020)

LCRPGR value during 2000-2010 suggested a decrease in land consumption rate despite population increases, with both metrics showing increases from 2010-2020 (Table 2). These observations reveal intricate dynamics between land consumption and population growth across Lahore's tehsils, underscoring the variability of these trends over time and their implications for urban planning and sustainable development.

DISCUSSION

The detailed land use changes depicted in Fig. 3(a) provide an exhaustive snapshot of Lahore's land cover composition in 1990, shedding light on the initial conditions of urban land, water bodies, barren land, and vegetation cover. To place these findings within a broader context and establish connections with other research endeavors, it is critical to reference studies that examine urbanization patterns, land dynamics, and environmental shifts in rapidly growing cities. The study by Jabbar & Yusoff (2022) on urbanization patterns and their impact on vegetation cover in developing megacities offers valuable insights that may corroborate the observed decrease in vegetation cover in Lahore from 1990 to 2000, demonstrating commonalities in trends amid swift urban expansion.

Furthermore, the investigation conducted by Hanif et al. (2023) into the environmental repercussions of urban growth, particularly in terms of the expansion of built-up areas, can enhance our understanding of the increase in built-up areas in Lahore from 2000 to 2020, enriching the discourse on urbanization dynamics. Additionally, the study and discussion by Jabbar et al. (2021) on the role of green spaces in mitigating urban heat island effects dovetails with the observations in Fig. 3(d), where an uptick in vegetation cover in Lahore in 2020 is noted. This reference may highlight the importance of fostering green spaces within rapidly urbanizing contexts.

The observed diminution in green spaces in Lahore, combined with rising population density, necessitates an in-depth examination of the nexus between urbanization, population growth, and vegetation cover. This study dives into this complex relationship by utilizing population data from various tehsils in Lahore spanning between 1990, 2000, 2010, and 2020. The findings unveil a consistent inverse correlation between population density and vegetation across all tehsils, with the decline in green spaces paralleling increases in population density, as illustrated in Fig. 10. This pattern corroborates with literature such as Dadvand et al. (2019), which articulates the challenges urbanization poses to green spaces and the imperative for sustainable urban planning. The analysis of land use and land cover changes demonstrates the clustering of urbanization around the walled city in the earlier decades, transitioning to intensified population growth in already populated areas in subsequent years. Notably, regions such as Shalimar, Cantonment, Gulberg, Samanabad, and Iqbal Town experienced accelerated urbanization, as evidenced in Figs. 3(c) and 3(d). These trends align with Jabbar & Mohd Yusoff's (2022) findings, accentuating the spatial dynamics of urban growth and its ramifications on population patterns.

The progression from 1990 to 2020 reveals a considerable expansion of urban territories to the detriment of vegetation, revealing the intricate interrelation between urbanization, population density, and the contraction of green spaces over time. This narrative resonates with the research of Duan et al. (2018), which suggests that the sprawl of urbanization detrimentally affects natural landscapes. Furthermore, the observed proliferation of vegetation from 2010 to 2020, alongside a reduction in barren land, hints at initiatives to weave green spaces into the fabric of urban development, resonating with studies like Aboulnaga & Mostafa (2020), which highlight the beneficial impacts of strategic urban development on green area conservation. In summary, this investigation contributes to the expanding collection of research and data that sheds light on the complex intersection among urbanization, population growth, and the conservation of green spaces. By contrasting these findings with existing scholarly works, the overall shared discourse emphasizes the necessity for integrated urban planning approaches that balance the needs of populations with environmental stewardship.

LIMITATIONS

A key limitation of this research is the reliance on population census data from only 1998 and 2017, potentially leading to inaccuracies in calculating growth rates for the specific geographic units under study. The use of population data from disparate years introduces uncertainty in the calculations of population density and the associated rates of change. Furthermore, potential changes in geographic unit boundaries over time present an additional challenge. Such alterations can result in errors when estimating population densities and, by extension, impact the precision of change rate calculations.

CONCLUSION

The study highlights the changes in land cover from 1990 to 2020 and offers a thorough analysis of Lahore's rapid development and reduction in vegetation. It clarifies how and in what ways human activity and natural processes can affect the urban environment. It also highlights the challenges posed by the growth and expansion of housing societies. The research provides valuable insights for stakeholders like the Environment Protection Department and the Lahore Development Authority through an

Table 2. The ratio of land consumption rate to population growth rate

LCRPGR	1990 – 2000	2000 - 2010	2010 - 2020
Lahore Cantt	1.576	0.18	0.154
Lahore City	0.999	0.16	0.146
Model Town	0.343	0.013	0.121
Raiwind	0.685	1.01	0.107
Shalimar	0.409	-0.491	0.209

urban landscape matrix analysis, leading to well-informed decision-making to prevent the loss of green spaces. The study also emphasizes how vital green spaces are to urban well-being and how crucial it is to incorporate these areas into plans for urban growth. It further accentuates the requirement of resilience and sustainability in urban planning and pushes for a balanced approach to regulating land use and population density. The study's recommendations emphasize the importance of remote sensing methods and spatiotemporal analysis for efficient urban planning and management. The concept proposes a financially viable model for continuous urban study and monitoring that utilizes publicly available satellite images for periodic analysis. It is recommended that policymakers give precedence to sustainable urbanization initiatives, ensuring that green space planning is incorporated into development initiatives. This strategy improves the well-being of residents and urban biodiversity, and it synchronizes Lahore's urban development with environmental conservation objectives. By implementing the strategies above, Lahore may balance urban growth with ecological integrity and create a resilient and sustainable urban future.

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