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Green Infrastructure and Socio-Environmental Implications for Urban Sustainability in North and South Delhi

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ABSTRACT

Rapid urbanization in Delhi has intensified pressure on urban infrastructure, environmental resources, and the overall quality of life of residents. This study assesses urban sustainability and quality of life in the North and South districts of Delhi by examining the role of green infrastructure and socio-environmental conditions. The research adopts a mixed-method approach combining household survey data, remote sensing analysis, and statistical techniques to evaluate spatial and socio-economic variations in urban sustainability. Vegetation dynamics were examined using satellite-derived vegetation indices, while primary survey data were used to evaluate access to basic urban services such as water supply, sanitation, healthcare, education, waste management, and income levels. The findings reveal notable spatial disparities in green infrastructure distribution and access to basic services between the two districts. South Delhi generally demonstrates better access to socio-economic resources and planned green spaces, while several areas in North Delhi face challenges related to infrastructure provision and service accessibility. The analysis highlights how differences in urban planning, socio-economic conditions, and infrastructure availability influence residents' quality of life and environmental sustainability. Overall, the study emphasizes the importance of integrating green infrastructure planning with equitable service provision to promote inclusive and sustainable urban development in rapidly expanding metropolitan regions such as Delhi.

Keywords: Urban Sustainability; Green Infrastructure; Quality of Life; Urban Inequality

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1. Introduction

Urbanization is an inevitable outcome of economic development and demographic transitions [1]. In India, urban growth has been particularly pronounced, with cities like Delhi witnessing massive population influxes, expansion of built-up areas, and escalating demands on infrastructure and natural resources [2]. As the urban population grows, so too does the pressure on housing, transportation, water supply, sanitation, and other civic amenities elements that are critical to a sustainable and healthy urban environment [3].

Delhi, being one of the most populous megacities in the world, provides a compelling case study for understanding the complex relationship between urban development and environmental sustainability [4]. With a population exceeding 20 million, the city faces severe challenges related to air and water pollution, inadequate waste disposal, shrinking green cover, and increasing socio-economic inequalities [5]. The situation is further compounded by uneven development across its various districts. North and South Delhi, for instance, represent two urban typologies: while South Delhi is relatively affluent and better resourced, North Delhi includes a mix of planned and resettlement colonies that often lack adequate infrastructure [4].

Enhancing human well-being while preserving environmental resources for future generations is known as urban sustainability [6,7]. By 2050, almost 70% of the world's population is predicted to reside in cities due to rising urbanisation, making sustainable urban planning imperative [8]. Reducing environmental effects while advancing social justice, liveability, and effective resource management are the main goals of urban sustainability [9]. In this regard, green infrastructure is crucial to enhancing the quality of the urban environment and the welfare of its inhabitants.

This study examines how sustainability programs and green infrastructure affect North and South Delhi's quality of life. The study evaluates important metrics such water availability, sanitation, income, education, healthcare access, and public perception using data from primary household surveys and remote sensing. Policymakers and urban planners can use the study's conclusions to support fair and ecologically sustainable urban growth.

2. Database and Research Methodology

2.1. Data Source and Methodology

Both primary and secondary data sources are used in the study. Institutions include the Delhi Urban Shelter Improvement Board (DUSIB), Delhi Development Authority (DDA), Ministry of Urban Development, Census of India, Directorate of Health Services, and National Institute of Urban Affairs (NIUA) provided secondary data.

A standardised questionnaire encompassing waste management, water supply and quality, sanitation, and public awareness was used to gather primary data [10,11]. Purposive random sampling was utilised to choose 400 respondents in total, and stratified sampling was employed to determine the study sites. Thematic analysis was used to assess qualitative responses, while descriptive statistics were used to analyse quantitative data. GIS and Microsoft Excel were used for data mapping and visualisation (**Figure 1**).

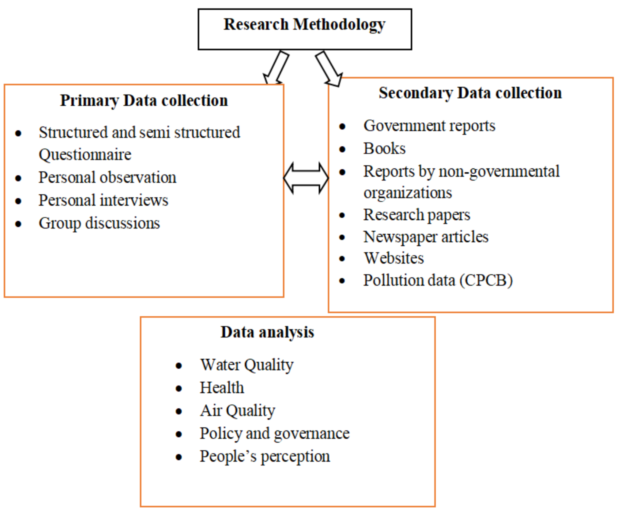


Figure 1. Flowchart of the Research Methodology.

To examine land use and vegetation cover, remote sensing data from Landsat satellites (2005, 2011, 2021) were utilised. Data from the USGS was obtained during the clear-sky months of January through February. To compute the Normalised Difference Vegetation Index (NDVI), the Townshend and Justice (1986) approach was used:

$$NDVI = (NIR - R)/(NIR + R)$$

Where NIR = Near Infrared Band and R = Red Band.

Values range from −1 to +1, with higher values indicating denser vegetation. NDVI thresholds used were 0.162 for 2005 and 0.155 for 2021.

2.2. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) is a statistical procedure which uses *F* test to investigate the difference in the means of a group of data or variables [12] (Equation (1)).

$$F = \frac{\text{Variation between sample mean}}{\text{Variation within the sample}} \tag{1}$$

2.3. Correlation Using Pearson's Coefficient

Correlation coefficient measures the strength of association between two variables of interest [13]. It depicts how one variable value changes with the increase and decrease of other. Measures of correlation have the characteristics of being dimensionless and scaled to lie in the range $-1 < r < 1$. When one variable is a measure of time or location, correlation becomes a test for temporal or spatial trend. The most commonly used measure of correlation is Pearson's *r*. It is also called the linear correlation coefficient because '*r*' measures the linear association between two variables [14]. If the data lie exactly along a straight line with positive slope, then $r = 1$. If *X* and *Y* are two variables, then the correlation '*r*' between the variable *X* and *Y* is given by Equation (2).

$$Correlation(r) = \frac{(x-\bar{x})}{\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2}} \tag{2}$$

Where, *x* and *y* are the sample means. If the value of correlation coefficient '*r*' between two variables *X* and *Y* is fairly large, it implies that these two variables are highly correlated.

3. Result and Discussion

To improve the quality of the urban environment, Delhi has implemented a multifaceted greening policy. Trees in the city are legally protected by the Delhi Preservation of Trees Act, 1994, which also allows the public to report illegal felling through a Tree Helpline [15]. The Forest Department oversees the implementation of plantation programs by a number of organisations, including MCD, PWD, DDA, NDMC, and DMRC.

As of 2021, Delhi's Forest and Tree Cover accounts for 19.97% of its geographical area (11.88% forest cover and 8.09% tree cover), a significant rise from 1.48% in 2005, despite a 31.8% increase in urban population (**Figure 2**). Parks and gardens serve vital recreational and educational roles, while the Delhi Development Authority has established two key biodiversity parks Yamuna and Aravalli, as part of the city's green infrastructure.

3.1. Urban Green Space in North and South Delhi

As illustrated in **Figure 3**, there are significant differences between North and South Delhi's urban green spaces. North Delhi exhibits a decentralised and community-based design, with around 1,920 ha of communal greenery and 941 ha of parks and green belts. South Delhi, on the other hand, is the greenest area of the city thanks to its organised green network, which includes 6,823 parks and the 6,200-hectare Delhi Ridge. In general, North Delhi's vegetation is more dispersed but locally important, whereas South Delhi's is more expansive and well-planned.

3.2. Spatial Pattern of NDVI in Delhi

The Normalized Difference Vegetation Index (NDVI) measures vegetation health using red and near-infrared (NIR) reflectance [16]. NDVI values range from −1 to +1, with higher values indicating healthy vegetation, around 0 showing built-up areas, and negative values representing water or barren land.

As illustrated in **Figure 4**, the study showed a significant increase in vegetation, with NDVI values rising from −0.1228 to 0.6387 in 2005 to 0.127–0.676 in 2021. Metropolitan areas had the lowest NDVI due to dense urbanization, while protected peripheral forests recorded the highest. Agricultural zones showed intermediate values, highlighting the crucial role of Delhi's peripheral green spaces in maintaining ecological balance.

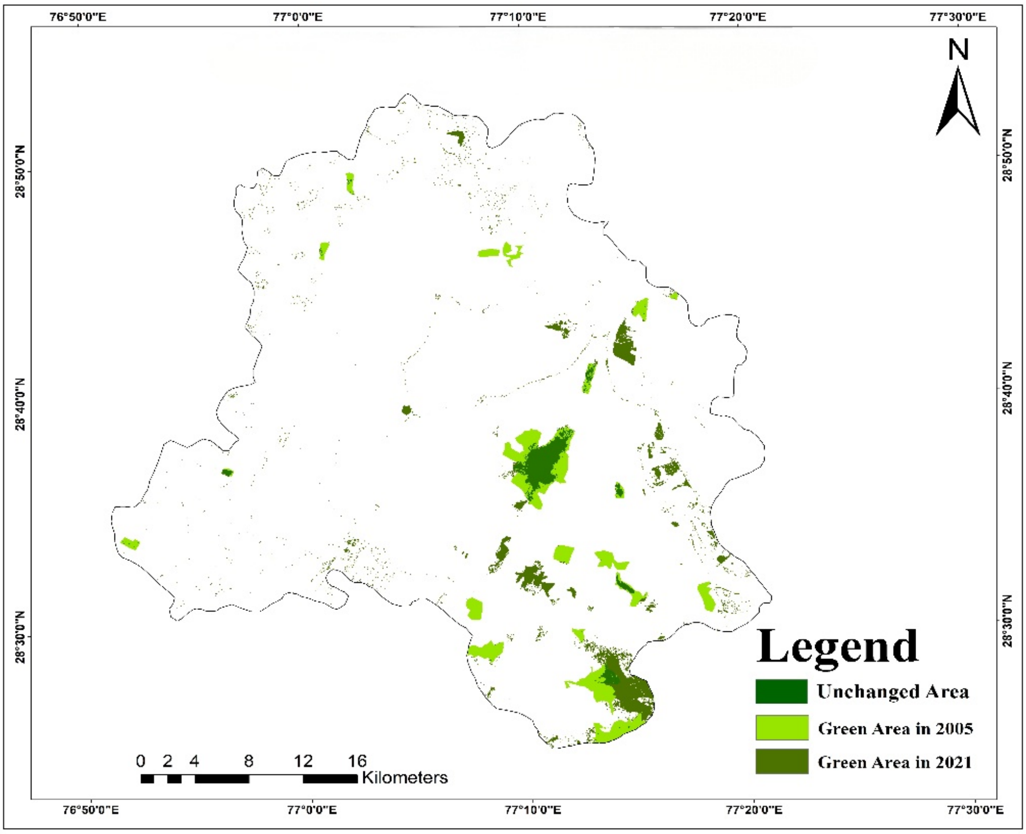
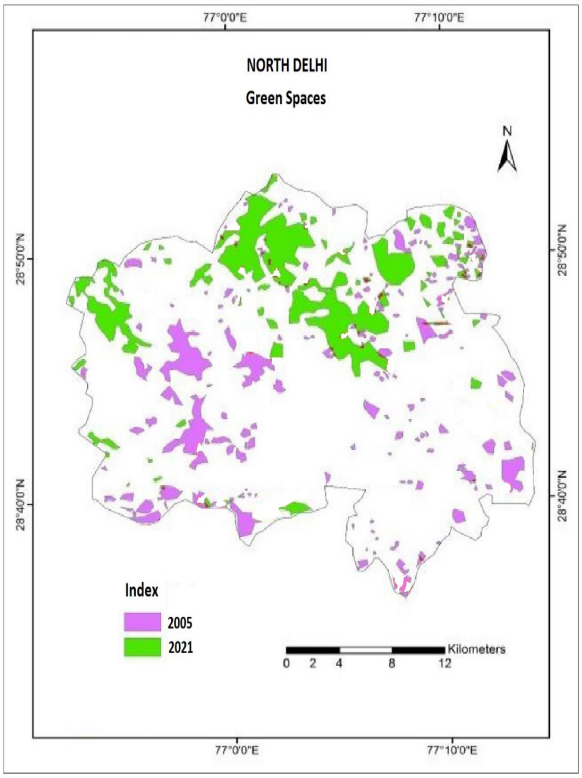
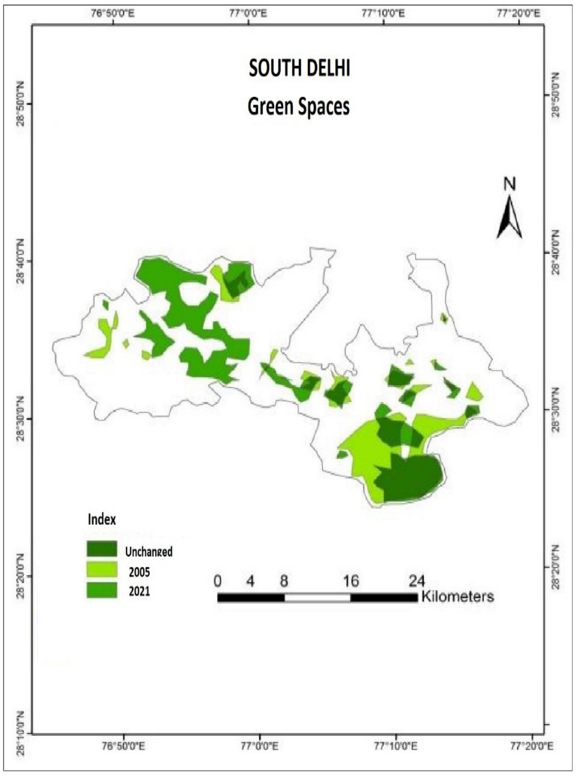


Figure 2. Change in Green area in Delhi and South Delhi (2005–2021).

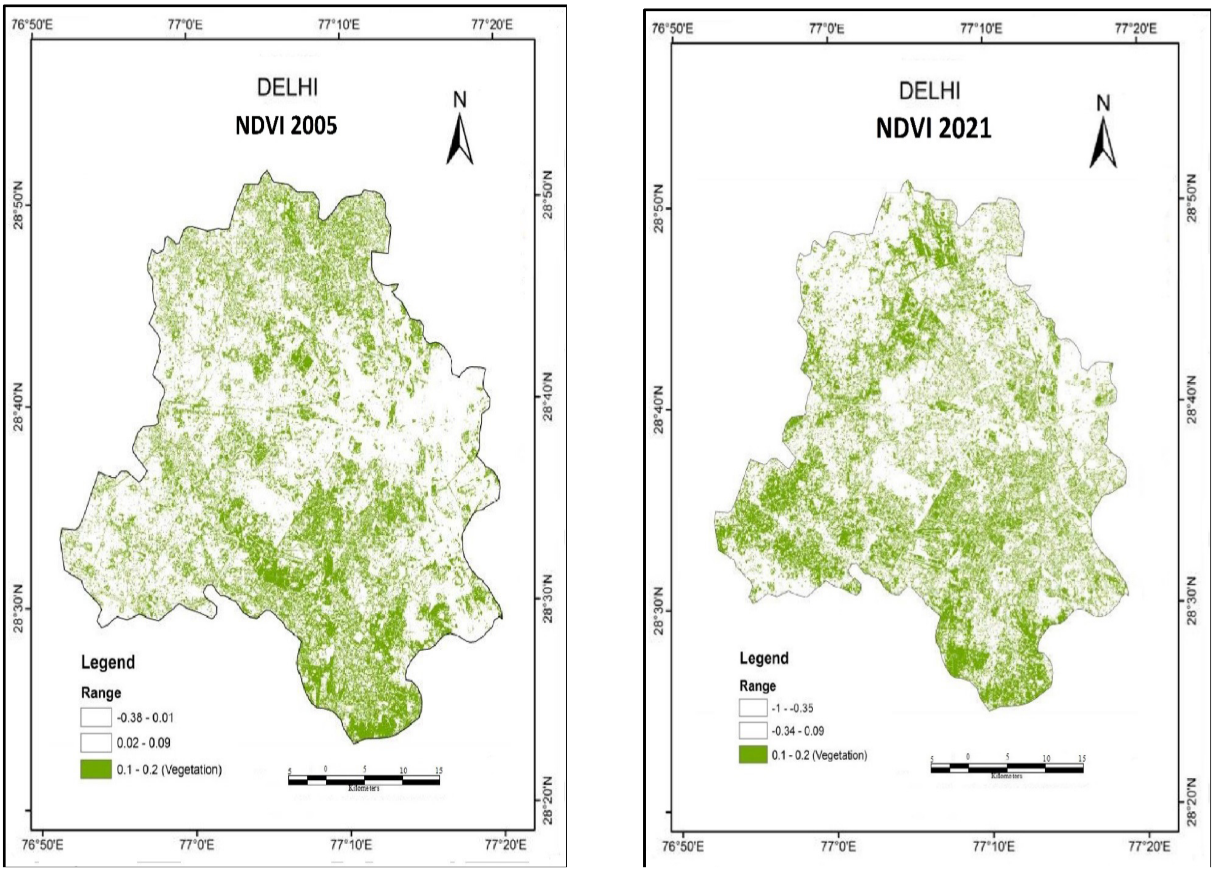


(**a**) Urban Green Spaces in North Delhi Districts.



(**b**) Urban Green Spaces in South Delhi District.

Figure 3. Urban Green Spaces in North Delhi and South Delhi Districts.



(**a**) NDVI of Delhi 2005. (**b**) NDVI of Delhi 2021.

Figure 4. NDVI of Delhi 2005, 2021.

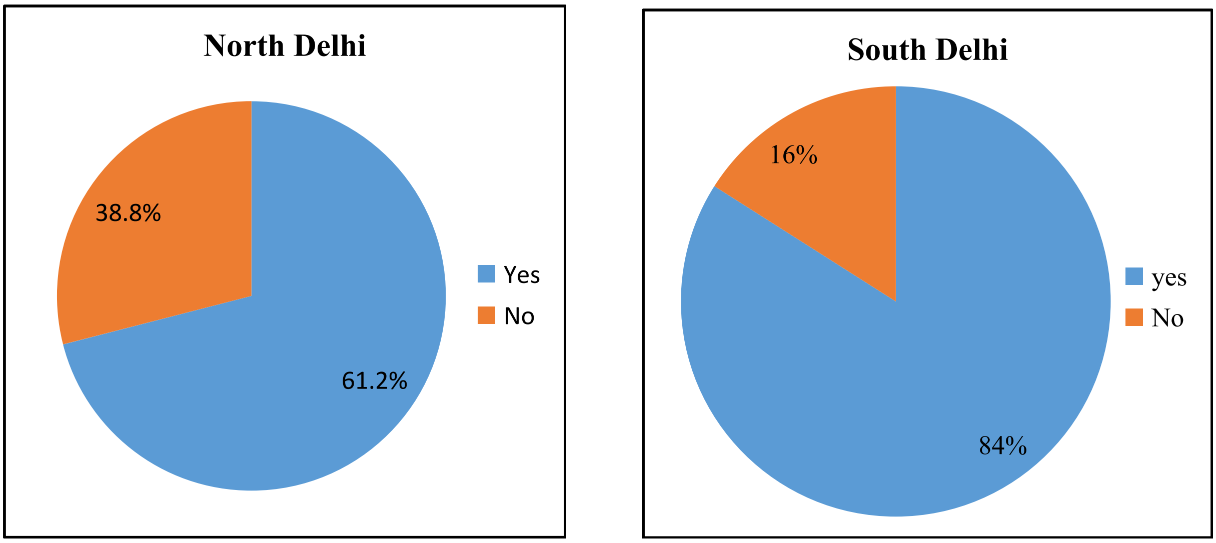
3.3. Basic Amenities and Their Sustainability

Civic facilities such as transport, water, electricity, sanitation, communication, training, and safety are essential for modern equitable communities [17]. However, if poorly planned, constructed, or maintained, they can harm the environment, human health, and create unequal access, highlighting the unintended consequences of civic infrastructure on sustainability.

3.4. Water Sustainability

Water supply in North and South Delhi shows significant inequalities, directly affecting residents' health and living standards. In North Delhi, 38.8% of households relied on other sources such as tankers, borewells, or hand pumps, while 61.2% had access to piped water from the Delhi Jal Board (**Figure 5a**). Resettlement colonies were especially affected, with few in-house connections and poor water quality, often light yellow, suggesting possible pollution. In South Delhi, 84% of respondents relied mainly on hand pumps, followed by water tankers and limited piped supply (**Figure 5b**). While both districts have unreliable systems, the issues differ: North Delhi faces problems with distribution and quality, whereas South Delhi struggles with access and source reliability, highlighting systemic challenges in urban water governance.

In the study areas, the satisfaction level for meeting demands of water was found that 31% of people having less than 25% of satisfaction with the present available water facilities. On the other side, only 11% of people responded that their satisfaction level is between 50–80% of present facilities. The breakdown of these responses is detailed in **Table 1**.



(**a**) Water Sustainability in North Delhi. (**b**) Water Sustainability in South Delhi.

Figure 5. Accessibility to Piped Water in North Delhi and South Delhi.

Table 1. People Perception for Water Sustainability in North Delhi.

North Delhi	Satisfaction of Water Sustainability (%)				Total (%)
	<25	25–50	50–80	>80	
Respondents	31.0	36.0	11.0	22.0	100

Source: Primary survey, 2021.

In South Delhi, those who have access to Delhi Jal Board water (very small proportion) responded that there are 84% respondents have water facilities at home by Delhi Jal Board. But as detailed in **Table 2** as per their satisfaction level for water sustainability it is 36% respondents has 25–50% satisfaction, 41% reported less than 25%, therefore the people were not found to be satisfied with the available water facilities.

Table 2. People Perception for Water Sustainability in South Delhi.

South Delhi	Satisfaction of Water Sustainability (%)				Total (%)
	<25	25–50	50–80	>80	
Respondents	41.0	36.0	10.0	13.0	100

Source: Primary survey, 2021.

3.5. Waste Disposal and Sustainability

Wastewater in Delhi's resettlement colonies primarily originates from domestic activities such as kitchens, bathing, and washing, with limited infrastructure for proper disposal [18]. In North Delhi, 68.5% of households reported using public drainage systems, but these are often clogged and overflowing, while 27.8% face wastewater accumulation within homes, and 3.7% are unaware of their drainage arrangements. As shown in **Figure 6**, South Delhi shows slightly better usage of public drains at 66.7%, yet maintenance problems like blockages and overflows remain widespread.

These deficiencies in drainage infrastructure, common in informal settlements, contribute to unsanitary living conditions and heighten the risk of waterborne diseases. Addressing these issues is essential for ensuring environmental sustainability and public health in both districts.

Figure 6. Disposal Issue in Delhi.

3.6. Quality of Life and Sustainability

Quality of life is a multidimensional concept that reflects the overall well-being of individuals and communities, extending beyond mere economic indicators like GDP [19]. Defined by the World Health Organization as an individual's perception of their position in life within cultural and social contexts, it encompasses factors such as income, education, health care access, and recreation. Modern understanding recognizes that material wealth alone does not ensure well-being; instead, quality of life includes social, environmental, and psychological dimensions, making it a vital metric for assessing human development and societal progress. In order to measure quality of life, one must have a theory of what makes up a good life [20].

3.7. Indicators and Features of Quality of Life

The study assessed Quality of Life (QoL) using eight key indicators based on WHO guidelines, combining objective and subjective measures. Indicators were selected to capture social wellbeing, excluding universally available facilities like street lighting and electricity in Delhi colonies. Data were collected through observations and respondent interactions to ensure reliability and contextual relevance. The indicators include: access to drinking water (individual or community taps); access to sanitation (private or public toilets); education level (primary to graduate); access to healthcare (government or private facilities); economic conditions (monthly household income and occupation); leisure (ownership of television and mobile phones); and environmental management (solid waste disposal).

The weighting values assigned to the Quality of Life indicators were determined based on the relative importance and accessibility of essential services in the study areas. Higher weight was given to access to government hospitals because they provide affordable and widely accessible healthcare for low- and middle-income households in the resettlement colonies of Delhi. In contrast, private healthcare services, although associated with higher economic status, are often less accessible due to higher costs. Therefore, the weighting system reflects the practical significance of basic services such as healthcare, water supply, sanitation, education, and income in determining the overall quality of life and urban sustainability in the study area.

3.7.1. Monthly Income

Income of a household is dominating indicator of quality of life [21]. The average monthly family income of the household surveyed ranges between Rs.7,000–10,000. Most of the male members of the households were found to working as labour at construction sites, as drivers, mechanics plumber etc. and the female members as maids in the nearby areas. The monthly income to some houses found to be in the range Rs.10,000 to 15,000 and to some in between Rs.5,000 to 8,000 respectively. The weightage given to income groups is given in **Table 3**.

Table 3. Weightage Value Given to Selected Variables.

S. No.	Indicator	Sub Category	Weightage
1.	Monthly Income (Rs.)	Less than 5,000	1
		5,000–10,000	2
		10,000–15,000	3
		More than 15,000	4
2.	Access to Healthcare	Government hospital	3
		Private hospital	2
		Other means	1
3.	Access to Education	Basic education	1
		Senior secondary	2
		Graduation	3
		Professional courses	4
		Illiterate	0
4.	Recreation (owning TV/Mobile)	Having Mobile/TV	1
		Don't have	0
5.	Occupation	Tertiary Sector	2
		Secondary sector	3
		Others	1
6.	Access to Drinking Water (Delhi Jal Board)	Delhi Jal Board	2
		Tanker and other Sources	1
7.	Access to Toilet	Yes	2
		No	1
8.	Waste Collection	Daily	2
		Weekly	1

Source: Primary survey, 2021.

3.7.2. Education Level

Literacy is a key indicator of cultural and socio-economic status, closely linked to Quality of Life [22]. In megacities like Delhi, access to educational facilities is a vital aspect of infrastructure. Studies show that higher literacy levels are essential for improving the social environment. In this study, low literacy is largely attributed to poverty and lack of awareness, with many individuals dropping out at the primary level. **Table 4** reflects that literate individuals, especially those employed in the tertiary sector (like peons, teachers, and drivers), are given higher weightage in the QoL assessment.

Table 4. Selected Variables with Quality of Life in Delhi.

S.No.	Indicators	North Delhi	South Delhi
1.	Income	0.7840	1.1410
2.	Access to Healthcare	0.6717	0.2667
3.	Access to Education	0.6868	1.4030
4.	Recreation	0.4830	0.3038
5.	Occupation	0.3349	0.4229
6.	Access to Drinking Water	0.4385	0.3162
7.	Access to Toilet	0.5006	0.4229
8.	Waste Collection	0.3386	0.4961
9.	Total	0.156	0.247

Source: Primary survey, 2021.

3.7.3. Occupation

The occupation and the economic status are related to each other; a positive co-relation is being observed between literacy and secondary workers. Occupation level to a larger extent contributes in Quality of Life improvement in human resources [23]. Families having at least 30% are engaged in tertiary jobs and maximum share of the population engaged in construction work as daily wage earners (**Table 4**).

3.7.4. Entertainment Facilities

Standard of living in the study is assessed through the ownership of household gadgets (TV, bicycle, mobile phone, DVD player) and access to basic amenities like room density, metered electricity, fuel source, and drinking water. Recreational facilities were measured by the presence of a television and mobile phone, with higher weightage (2) given to households possessing both, and lower weightage (1) to those without. Around 90% of households own TVs and mobile phones. However, despite this, all four selected resettlement colonies still lack full access to recreational facilities.

3.7.5. Medical Facilities

Occurrence of diseases is a common phenomenon in all the resettlement colonies. For treatment, the people of resettlement colonies depend primarily on private clinics and hospitals but significant section of population refer government hospital and few people still follow the traditional methods of treatment by referring 'Baids'. The households amounting around 56% of the total number of households depend on government hospitals due to the low cost of treatment (**Table 4**). They are, however, satisfied with the existing medical services. But they want timely treatment as at times no doctor is available during the late night hours.

3.7.6. Access to Drinking Water

Safe and pure drinking water is basic need for life [24]. The water quality and health are positively correlated to each other, followed by the correlation between the health and the economic status (**Table 4**). Therefore, directly or indirectly almost every indicators mentioned above are related to each other and together determining the quality of life. In the four resettlement colonies surveyed, only 61% of the household have access to Delhi Jal Board water and remaining 38% either have access to hand pumps or water tankers.

3.7.7. Access to Toilet

Sanitation is not only important for healthy living but also ensuring a non-polluted environment for that accessibility to toilet is an important indicator to be taken into consideration [25]. As per the survey, still significant proportion of the households doesn't have access to toilet facilities (**Table 4**). There is positive relationship between the accessibility to toilet and quality of life. Some of the respondent, feel that having toilet is matter of pride while some think it is not necessary. The reasons for not having access to toilets are lack of space, economic reasons, lack of awareness, etc.

3.7.8. Waste Collection

Solid waste needs to be collected regularly to prevent households from dumping their daily waste [26]. The consequences observed for the improper waste collection on the roadside results in bad odour, creating a breeding place for mosquitoes. Therefore, in the four resettlement colonies 25% households responded for waste collected twice a week and 70% for daily waste collection.

3.8. Scaling of Quality of Life

To explore variation in Quality of Life in four colonies, quantitative analysis of data has been done. The qualitative and quantitative processing is fully justified and the four levels of quality of life have emerged [27], North Delhi enjoys good quality of life than the other resettlement colonies as on an average all families surveyed, found to be in medium Quality of Life. In North Delhi out of total 200 households taken, seven household enjoy high quality of life as the computed standard deviation value is more than 1 (**Table 5**). In South Delhi out of total families taken 76 household included in high quality of life, eighteen families are found to be in medium quality of life and remaining seven in low quality of life.

Table 5. Level of Quality of Life in Delhi.

S. No.	Level of Quality of Life	North Delhi Districts	South Delhi Districts
1.	High (More than 1)	41	76
2.	Medium (0.67–1.00)	120	80
3.	Low (less than 0.67)	39	44
	Total	200	200

Source: Primary survey, 2021.

The computed standard deviation value depicting the level of Quality of Life, depicting low for North Delhi with the value 0.15 and high in South Delhi with 0.24 for with better income, education level, access to medical facilities but the area lacks in better toilet and water facilities (**Table 5**).

4. COVID-19 and Urban Sustainability

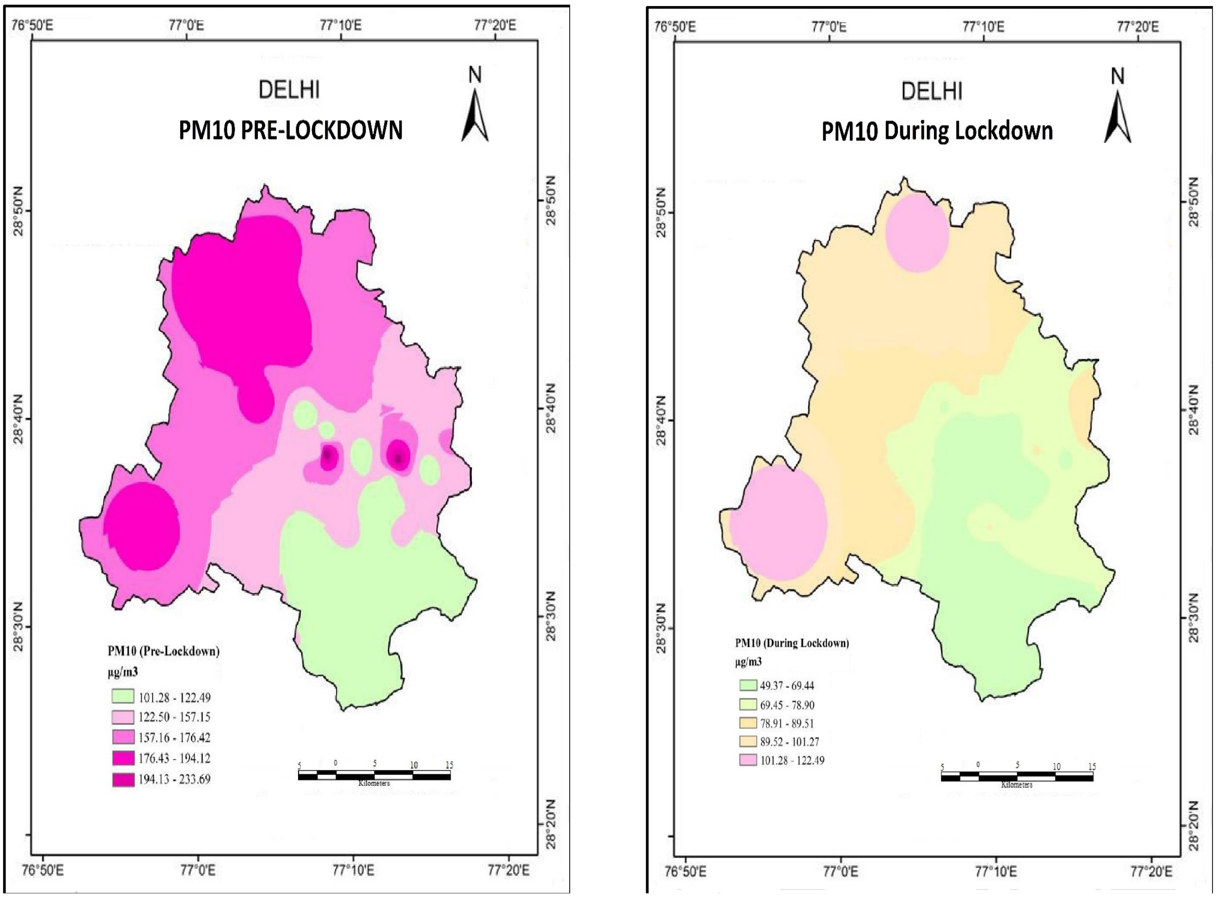
COVID-19 pandemic has touched all spheres of human life [28]. While it has been disastrous, the lockdowns enforced for control of the COVID-19 spread have resulted in significant air quality improvement. India went under a lockdown on 24th March 2020 initially for 21 days. Later, on 14th April 2020, the nationwide lockdown was extended till 3rd May, with some conditional relaxations in some areas after 20th April 2020. The lockdowns were further extended on 1st May by two weeks until 17th May. Various districts in the country were divided into three categories based on the corona virus's spread green, red, and orange. Lastly, lockdowns got extended from 17th May till 31st May. The restrictions were gradually lifted thereafter, with continued restrictions in the containment zones [29].

5. Air Pollution during COVID-19

The concentrations of air pollutants of PM10 pollutants before (12–22 March 2020) and during the lockdown

(23 March–2 April 2020). It must be noted that only one class overlapped between the two periods of analysis, i.e., 101.28–122.49. This class has been provided the same color scheme in pre-lockdown period and during lockdown period.

During the COVID-19 shutdown, Delhi's PM_{10} concentrations significantly decreased as a result of fewer human activities. PM_{10} levels were between 101.28 and 233.69 μg/m^3 prior to the lockout; during the lockdown, they decreased to 49.37–122.49 μg/m^3, a nearly 50% decrease (**Figure 7**). West Delhi had the smallest decrease (28%), while Shahdara district had the biggest (46%). Despite this improvement, South, New Delhi, and Southeast districts reported the lowest AQI values (82–84), while North Delhi had the highest mean AQI readings both before (161) and during (112) the lockdown.

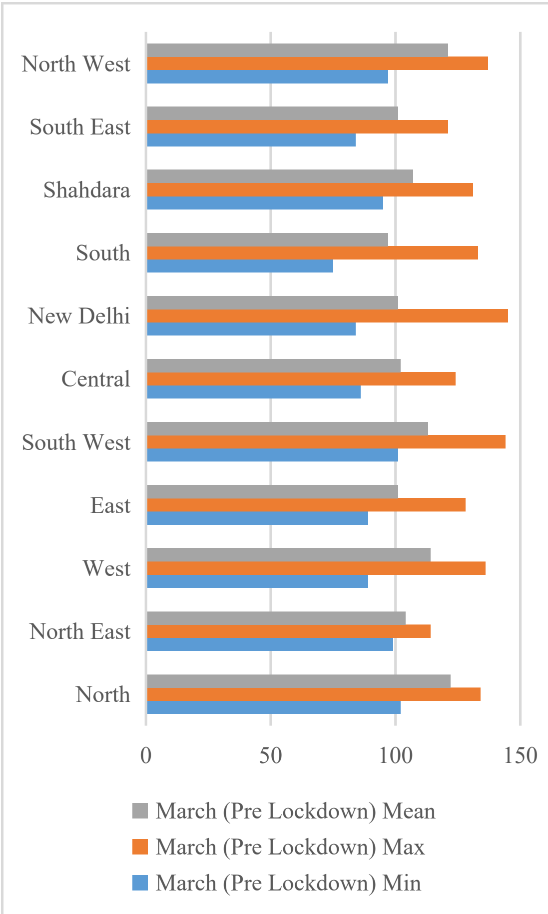


(**a**) PM_{10} Pre-Lockdown. (**b**) PM_{10} during Lockdown.

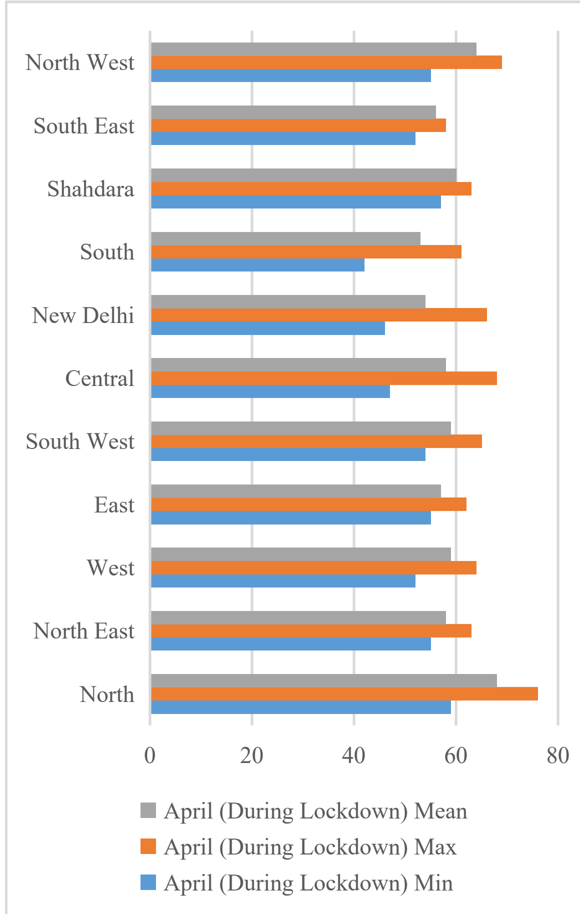
Figure 7. PM_{10} during Pre-Lockdown and Lockdown in Delhi.

Nitrogen-based pollution, however, were less impacted, perhaps as a result of ongoing domestic and energy-related operations. As a natural experiment, the lockdown demonstrated the significant impact of human emissions on Delhi's air quality and the possibility of cleaner air through efficient environmental control [30].

As illustrated in **Figure 8**, which compares the air quality in Delhi before and during lockdown, COVID-19 lockout measures restricted the combustion of diesel, petrol and other petroleum fuels, NOx emissions were considerably lowered in both industrialised and developing countries. Air quality significantly improved as transportation and industrial activity decreased, according to several studies. However, increasing levels of particulate matter and pollutant gases (NOx, SOx, and CO) have once again presented significant risks to the environment and public health in the post-COVID era. Public health, monsoon dynamics, and the radiation balance are all impacted by aerosols, and long-term exposure to pollution raises cardiovascular mortality. According to the National Ambient Air Quality Monitoring Programme, PM_{10} emissions continue to be the highest in India, followed by NO_2, SO_2, and CO.



(**a**) Air Quality in Delhi before Lockdown.



(**b**) Air Quality in Delhi during Lockdown.

Figure 8. Air Quality in Delhi before Lockdown and during Lockdown.

6. Water Pollution during COVID-19

The average values of pH of the Delhi's water were found to be 7.53, 7.26, and 7.64 for pre-lockdown, during the lockdown and post-lockdown periods, respectively. The maximum pH values were reported to be 7.77, 7.80, and 7.81 during these three time periods (**Table 6**). Moreover, the pH values for all the monitoring stations were the lowest during the lockdown period.

The pH values of Delhi's water remained alkaline, ranging from 7.2 to 7.8 across the pre-, during, and post-lockdown periods, and remained within the permissible limit of 6.5–8.5. During the lockdown, Biochemical Oxygen Demand (BOD) showed a significant decline due to reduced industrial discharge. The mean BOD values were 39.62 mg/L (pre-lockdown), 30.33 mg/L (during lockdown), and 40.50 mg/L (post-lockdown), indicating a 30.32% decrease during the lockdown and a 39.5% increase afterward, largely due to the resumption of domestic sewage and anthropogenic activities.

Table 6. Water Quality Assessment Pre, during and Post Lockdown.

Parameter	Pre-Lockdown			During-Lockdown			Post-Lockdown		
	Average	Max	Min	Average	Max	Min	Average	Max	Min
pH	7.53	7.77	7.27	7.26	7.80	6.59	7.64	7.80	6.59
TSS	57.2	178.00	6.00	30.33	160.00	5.00	60.40	256.00	8.00
BOD	39.62	100.00	8.00	31.32	250.00	1.30	40.50	180.00	2.80
COD	116.52	322.00	6.80	136.07	784.00	6.40	148.69	724.00	8.80
Conductivity	1,743.01	3,310.00	8.10	1,500.24	3,020.00	7.10	1,467.39	3,290.00	7.20

Similarly, Chemical Oxygen Demand (COD) levels increased after the lockdown. The mean COD values were 116.52, 136.07, and 148.69 mg/L for pre-, during, and post-lockdown periods, respectively, with maximum values reaching 322, 784, and 724 mg/L. These results highlight the strong influence of industrial and wastewater discharge on Delhi's water quality.

7. Multivariate Analysis

Multivariate analysis is a statistical approach that examines two or more variables simultaneously, helping identify patterns among complex factors in environmental systems. This simplifies complex phenomena and extracts key information to guide effective management and control policies [31]. In this study, Principal Component Analysis (PCA) was applied to water quality data to identify variables causing the largest variance and potential pollution sources. Data suitability for PCA was tested using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. KMO evaluates sampling adequacy, with values above 0.5 considered acceptable; the study's KMO value of 0.711 confirms PCA suitability. Bartlett's test assesses whether variables are correlated or independent. The significance level which is 0 (**Table 7**) in this study (less than 0.05) indicates that there are significant relationships among variables and can be clustered together.

Table 7. Kaiser-Meyer-Olkin measures and Barlett's test of Sphericity.

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.711
Bartlett's Test of Sphericity	Approx. Chi-Square	90.05
	df*	190
	Sig.*	0.000

Note: df*: degrees of freedom and Sig*: significance.

Principal Component Analysis (PCA) for Assessing Urban Sustainability

To the complex relationships among key indicators of urban quality of life and sustainability in North and South Delhi, Principal Component Analysis (PCA) was applied. PCA reduces data dimensionality by transforming interrelated variables into a smaller set of uncorrelated principal components that capture most of the variation in the dataset [32].

Mathematically, each principal component (PC) is computed as:

$$PC_i = a_{i1}X_1 + a_{i2}X_2 + \ldots + a_{ij}X_p \tag{3}$$

Where:

- PC_i = i-th principal component,
- $X_1, X_2, ..., X_p$ = original standardized variables,
- a_{ij} = loading of variable j on principal component i.

The analysis used eight primary survey variables income, healthcare, education, recreation, occupation, drinking water, toilet access, and waste collection. Data from both districts were standardized to remove scale bias. The KMO value (0.72) and Bartlett's Test ($p < 0.001$) confirmed the dataset's suitability for PCA. Using Varimax rotation with Kaiser normalization, three principal components were extracted with eigenvalues greater than 1, explaining 78.3% of the total variance. The rotated component matrix, detailed below in **Table 8**, revealed the following latent dimensions:

Table 8. Principal Component Analysis Matrix (PCA Results).

Variable	Component 1 (Socio-Economic)	Component 2 (Infrastructure Services)	Component 3 (Recreational Access)
Monthly Income	0.851	0.122	0.044
Access to Healthcare	0.812	0.201	−0.065
Access to Education	0.796	0.103	0.052
Occupation	0.754	−0.106	0.108
Access to Drinking Water	0.109	0.812	0.025
Access to Toilet	0.132	0.780	−0.059
Waste Collection	0.145	0.728	−0.011
Recreation (TV/Mobile)	0.065	0.031	0.822

Source: Calculated by authors, based on primary survey, 2021.

PCA identified key factors shaping urban quality of life and sustainability in North and South Delhi. The results show that socio-economic development and infrastructural access are the main determinants of urban sustainability. While South Delhi performs better socio-economically, both regions face challenges in water and sanitation. These findings offer an evidence base for policies promoting economic inclusion and equitable infrastructure for sustainable urban development.

8. Chi-Square Test Matrix for Urban Sustainability

A Chi-Square Test of Independence was used to analyze district-wise variations in key urban sustainability indicators between North and South Delhi. The test examined associations between district and categorical variables such as water supply satisfaction, sanitation, healthcare access, income, and education levels derived from the primary survey.

The Chi-Square test results reveal statistically significant disparities between North and South Delhi across several key urban sustainability indicators. For instance, access to toilets shows a significant association with district ($\chi^2 = 6.92$, $p = 0.008$), indicating uneven sanitation infrastructure across the two regions. Although sanitation facilities have improved in recent years, many resettlement colonies in North Delhi still rely on shared or public toilets due to space constraints and limited household infrastructure. Waste collection frequency also shows a significant relationship with district ($\chi^2 = 4.34$, $p = 0.037$), suggesting differences in municipal service efficiency. South Delhi, which largely consists of planned residential colonies and relatively affluent neighbourhoods, tends to receive more regular waste collection services compared to densely populated settlements in North Delhi (**Table 9**).

Table 9. Chi-Square Test Matrix.

Indicator	Chi-Square Value (χ^2)	Degrees of Freedom (df)	*p*-Value
Satisfaction with Water Supply	5.59	3	0.133
Access to Toilet	6.92	1	0.008
Waste Collection Frequency	4.34	1	0.037
Access to Healthcare Type	18.91	2	<0.001
Access to Education Level	20.18	3	<0.001
Occupation Type	2.16	2	0.339
Ownership of TV/Mobile	1.62	1	0.203
Monthly Income Group	8.27	3	0.041

Source: Calculate by Authors, based on Primary Survey, 2021.

Monthly household income further reinforces this socio-economic disparity ($\chi^2 = 8.27$, $p = 0.041$), where South Delhi households tend to fall into higher income categories compared to those in North Delhi, where many respondents are engaged in informal or daily wage occupations. In contrast, variables such as satisfaction with water supply ($\chi^2 = 5.59$, $p = 0.133$), occupation type ($\chi^2 = 2.16$, $p = 0.339$), and ownership of TV/mobile devices ($\chi^2 = 1.62$, $p = 0.203$) do not show statistically significant associations, suggesting that these aspects reflect broader city-wide conditions rather than district-specific differences. The results highlight that the observed disparities are not merely statistical but reflect deeper structural inequalities in urban planning, infrastructure provision, and socio-economic development between North and South Delhi. Such spatial inequalities emphasize the need for targeted urban policies that prioritize equitable infrastructure development, improved service delivery, and inclusive urban sustainability strategies across different districts of Delhi.

9. Conclusions

This study examined the relationship between green infrastructure, urban sustainability, and quality of life in the North and South districts of Delhi. The findings indicate that green infrastructure plays an important role in improving environmental quality, supporting urban ecological balance, and enhancing the overall well-being of urban communities. Areas with relatively better planned green spaces, such as parks, green belts, and the Delhi Ridge, contribute to improved environmental conditions and recreational opportunities, which positively influence residents' quality of life. In contrast, several densely populated settlements in North Delhi experience limited access to green spaces and basic urban services, which affects environmental quality and living conditions. The analysis also reveals that disparities in socio-economic conditions, infrastructure provision, and urban planning contribute to variations in quality of life between the two districts. While South Delhi generally benefits from more organized green infrastructure networks and better access to services, parts of North Delhi face challenges related to sanitation, waste management, and access to healthcare and education. These findings highlight the importance of integrating environmental planning with social and infrastructural development to promote balanced urban sustainability. To improve the quality of life of Delhi residents, urban planning strategies should prioritize the equitable distribution of green infrastructure across different districts, particularly in densely populated and underserved areas. Strengthening community-level green spaces, improving waste management and sanitation infrastructure, and enhancing access to affordable healthcare and education are essential steps toward achieving inclusive urban sustainability. Furthermore, coordinated policy interventions involving municipal authorities, urban planners, and local communities can support the development of environmentally resilient and socially inclusive urban environments in Delhi.

Author Contributions

N. was written the conceptualization, data collection, formal analysis, manuscript writing of the draft. S.A. is provided supervision, guidance in research design, critical revision of the manuscript, and final approval. Both authors have read and approved the final version of the manuscript.

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Institutional Review Board Statement

The present study is based on a minimal-risk social and behavioral research design involving questionnaire-based primary data collection. According to the ICMR National Ethical Guidelines for Biomedical and Health Research involving Human Participants (2017), ethical approval and written informed consent are not mandatory for minimal-risk social science research that does not involve clinical intervention, biological samples, or sensitive personal identifiers.

Informed Consent Statement

Participation in the survey was voluntary, and verbal informed consent was obtained from all respondents prior to data collection. Confidentiality and anonymity of the participants were strictly maintained throughout the study.

Data Availability Statement

The data used in this study were obtained from publicly accessible sources. Specifically, NDVI data for Delhi (2005 and 2021), decadal changes in green areas, and urban green spaces for North and South Delhi districts were retrieved from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). Additionally, MODIS satellite data (https://modis.gsfc.nasa.gov/data/) were used for analyzing PM_{10} levels during the Pre-Lockdown and Lockdown periods in Delhi. All data generated or analyzed during this study are included in this published article.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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