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An analysis of air pollution trends in Jaipur, UNESCO world heritage city

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ABSTRACT

Introduction: Introduction: Air pollution is a significant environmental challenge globally, exacerbated by industrialization and increasing vehicular emissions. This study focuses on Jaipur, India, where rapid urbanization and industrial growth have intensified pollution levels, impacting public health and environmental quality.

Materials and methods: This study utilized secondary data from the Rajasthan State Pollution Control Board and satellite imagery obtained from the NRSC BHUVAN. Geographic Information System (GIS) tools were employed to analyze pollution data from six sample sites in Jaipur. Interpolation techniques, including Kriging and Inverse Distance Weighting (IDW), were used to map the spatial distribution of pollutants.

Results: From 2011 to 2019, Jaipur experienced varying levels of air pollution, with high concentrations of Particulate Matter (PM_{10}), Sulfur dioxide (SO_2), and Nitrogen dioxide (NO_2) observed in industrial and commercial zones, such as the Vishwakarma Industrial Area and Ajmeri Gate. Areas with natural features, like Jhalana Dungri and the Malaviya Industrial Area, consistently showed lower pollution levels.

Conclusion: The study highlights significant spatial and temporal variations in air quality across Jaipur, influenced by industrial activities and vehicular emissions. Effective pollution control measures and urban planning strategies are essential to mitigate the adverse impacts of air pollution on public health and environmental sustainability in Jaipur and similar urban centers.

Introduction

Environmental degradation has become a major global problem, particularly concerning air pollution. Since the Industrial Revolution, air pollution has increased rapidly due to large industries emitting substantial amounts of carbon dioxide and suspended particles into the atmosphere as byproducts of burning fossil

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fuels [1, 2]. Additionally, industries release many harmful gases and aerosols. Recently, vehicular pollution has escalated with the rising number of vehicles. It is evident that pollution is a significant issue globally [3, 4]. According to a World Health Organization (WHO) report, seven million people die annually due to air pollution, affecting 9 out of 10 people worldwide. All countries are working to control air pollution and improve air quality under the guidance of the World Health Organization. Environmental pollution is a common issue in both developed and developing countries. Each year, substantial quantities of solid waste are released into the atmosphere through the burning of fossil fuels, industrial and domestic waste, and vehicle emissions. In developing nations, urban areas face an environmental emergency primarily due to vehicular emissions, which contribute to 40-80% of total air pollution [5, 6].

In India, air pollution, especially in the northern region, has become a critical issue. The country has 23 significant urban areas with populations exceeding one million, many of which do not meet WHO air quality standards [5, 7]. According to a study, industry contributes 51% to air pollution, vehicle emissions 22%, biomass burning from crops 8%, and other activities-such as household waste, construction, dust storms, and fireworks during festivals-contribute 5%. Air pollution has become a subject of serious discussion due to the rapid increases in human activity in India. Industrialization has led to a daily increase in air pollution, driven by population growth, rising vehicle numbers, biofuel consumption, poor land use patterns, and inadequate infrastructure management [8]. A recent study, "Early Life Exposure to Outdoor Air Pollution: Effects on Child Health in India," found that Particulate Matters ($PM_{2.5}$) affects fetal development, reducing fetal length by 7.9% and weight by 6.7% in the first three months [9].

In India, the main air pollutants are Sulfur dioxide (SO_2), Nitrogen dioxide (NO_2), and Suspended Particulate Matter (SPM) [10, 11]. Urban areas are particularly exposed to high levels of air pollution, including metals, due to vehicle emissions, which are the primary source of fine and ultrafine particles [12, 13]. Diesel and petrol fumes from fossil fuels contain harmful substances [14].

Like many Indian cities, Jaipur is facing significant challenges, including urbanization, industrial emissions, traffic congestion, and poor road conditions [15]. These issues, along with its appeal as a tourist destination, have contributed to increased air pollution levels. Similar to other rapidly expanding cities in the nation, Jaipur is experiencing heightened urban development, traffic problems, inadequate infrastructure, and weak regulations on industrial emissions, all of which have adversely affected air quality [16]. While air pollution in the city originates from various sources, a comprehensive analysis of the chemical composition of PM_{10} and $PM_{2.5}$ has not yet been performed to identify these sources and their impacts [17]. This emphasizes the critical need to evaluate both gaseous and particulate pollutants over time and across different areas to shape policies and management strategies aimed at reducing air pollution in Jaipur.

Air quality index (AQI)

The Air Quality Index (AQI) is a daily measure that indicates air quality and its impact on health over a short period. It helps people understand how ambient air quality affects their health [18]. The Environmental Protection Agency (EPA) of the United States calculates the AQI for five common air pollutants, based on national air quality standards designed to protect public health: SO_2, NO_2, CO, O_3, and PMs (2.5 and 10) [19-21]. Categories of air quality index are shown in Table 1.

Different countries use various methods to calculate air quality; India employs a 500-point scale for its AQI.

Table 1. Categories of air quality index

Value	Type
0-50	Good
51-100	Satisfactory
101-200	Moderately
201-300	Poor
301-400	Very Poor
401-500	Severe

Objectives

* To assess distribution of NO_2, PM_{10}, SO_2 concentration in Jaipur city

* To estimate air quality index of Jaipur city

Materials and methods

This study relies on secondary data collected from various sources. Satellite imagery of Jaipur city was obtained from NRSC BHUVAN, while pollution data was sourced from the Rajasthan State Pollution Control Board (RSPCB) in Jaipur, Rajasthan. The study encompasses six sample sites designated by the RSPCB to assess pollution levels across different categories, such as industrial and commercial (see Table 2). Data collection followed a standardized procedure, involving the calculation of the annual arithmetic mean based on a minimum of 104 measurements per year at each site, taken twice a week at 24-h intervals. Upon collection, the raw data provided by the pollution control board were classified and converted into point data. Geographic coordinates were assigned using the ARC Map Tool. The satellite imagery obtained from NRSC BHUVAN was processed into SHP (Shapefile) format and incorporated into the ARC Map Tool, ensuring that all data elements were standardized to a consistent projection. Geographic Information System (GIS) analysis was performed using ARC Map Tool version 10.4. Point data and SHP files were integrated into the tool and aligned with a uniform projection for spatial analysis. The point data were further processed for export, and interpolation techniques such as Kriging and Inverse Distance Weighting (IDW) were applied to spatially distribute air pollution across Jaipur city. Kriging is an interpolation technique that predicts the value of a variable at an unmeasured site based on values from nearby locations [22]. IDW, on the other hand, produces more accurate estimates of PM by weighting measurement data based on distance [23]. After interpolation, the resultant data were formatted into map layouts for visualization and analysis. Methodological flowchart is shown in Fig. 1.

Table 2. Air quality monitoring sample sites of Jaipur city

Sl. No.	Sample sites	Categories
1	Vishwakarma	Industrial area
2	Malaviya	Industrial area
3	Regional Office	Commercial area
4	Jhalana Dungri	Commercial area
5	Ajmeri Gate	Commercial area
6	Chandpole	Commercial area

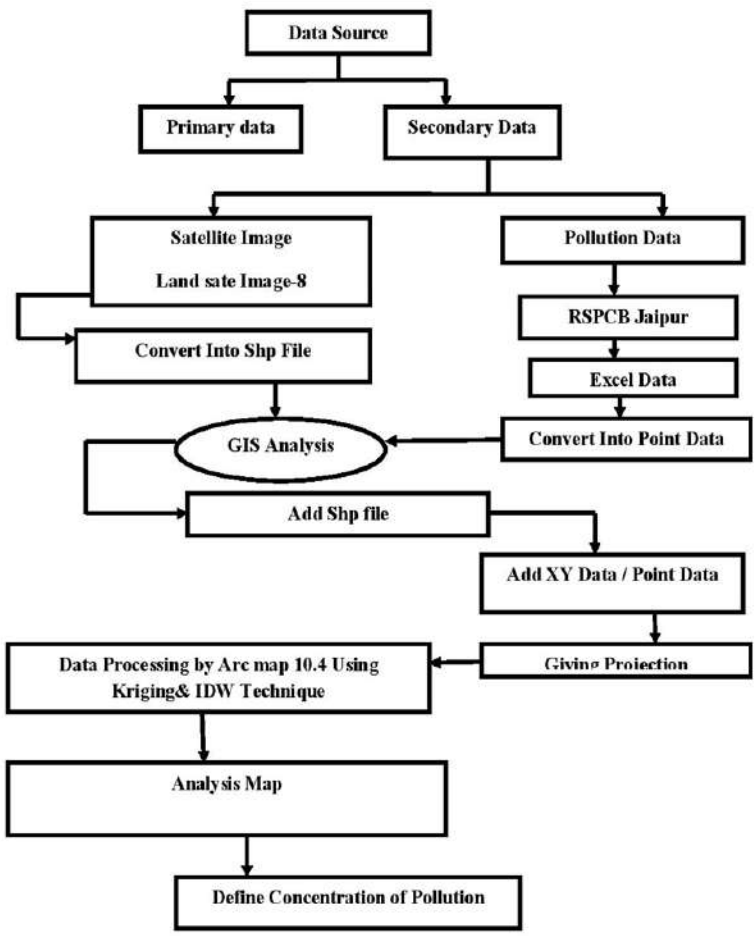


Fig. 1. Methodological flowchart

Study area

Geographically located in the northwestern part of India, Rajasthan extends between latitudes 23° 30' N and 30° 11' N, and longitudes 69° 29' E and 78° 17' E. Jaipur, the capital and historic city of Rajasthan, is situated in Northern India. According to the 2011 census, Jaipur city has a total population of 3.1 million, making it the 10th most populous city in India. Known as the "Pink City" due to the predominant pink color of its buildings, Jaipur is located approximately 268 km from New Delhi. It is a prominent tourist destination and forms a key part of the Golden Triangle tourist circuit, along with Delhi and Agra (240 km away). The city boasts two United Nations Educational, Scientific and Cultural Organization (UNESCO) world heritage sites: the Amer Fort and the Jantar Mantar Observatory [24, 25]. Location map of the study area is shown in Fig. 2.

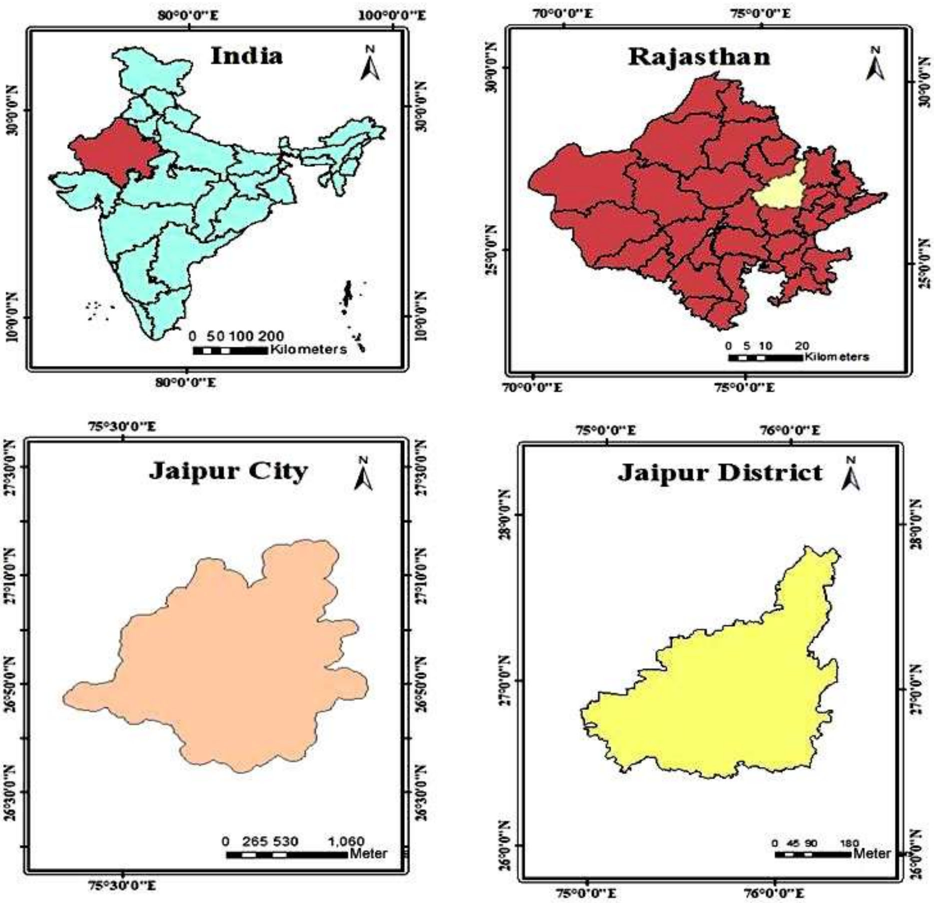
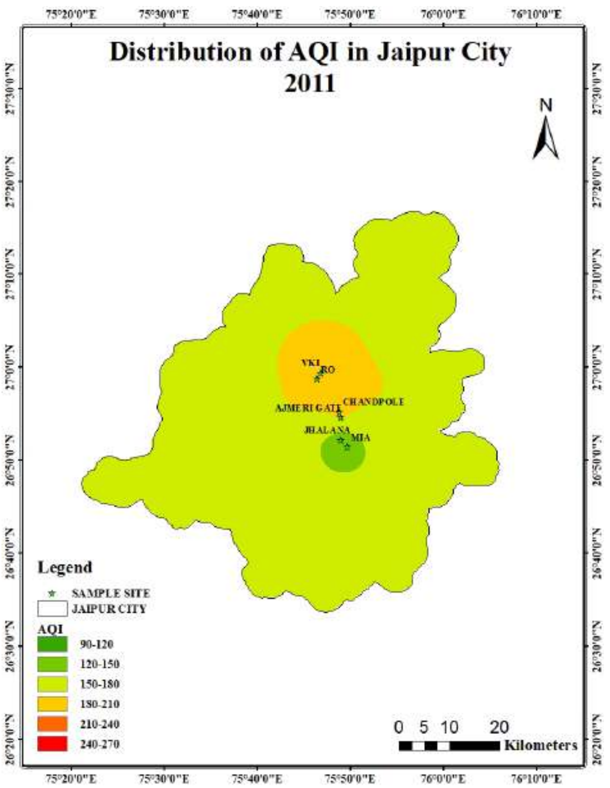


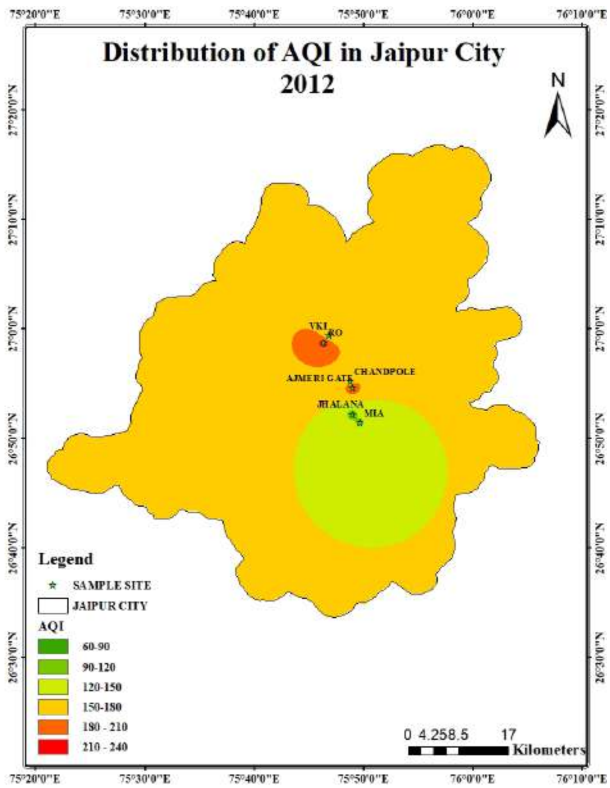
Fig. 2. Location map of the study area

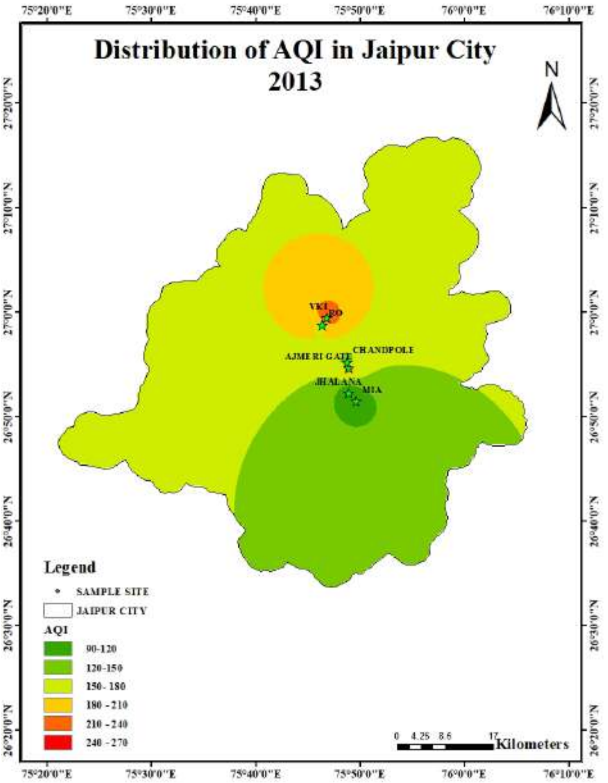
Results and discussion

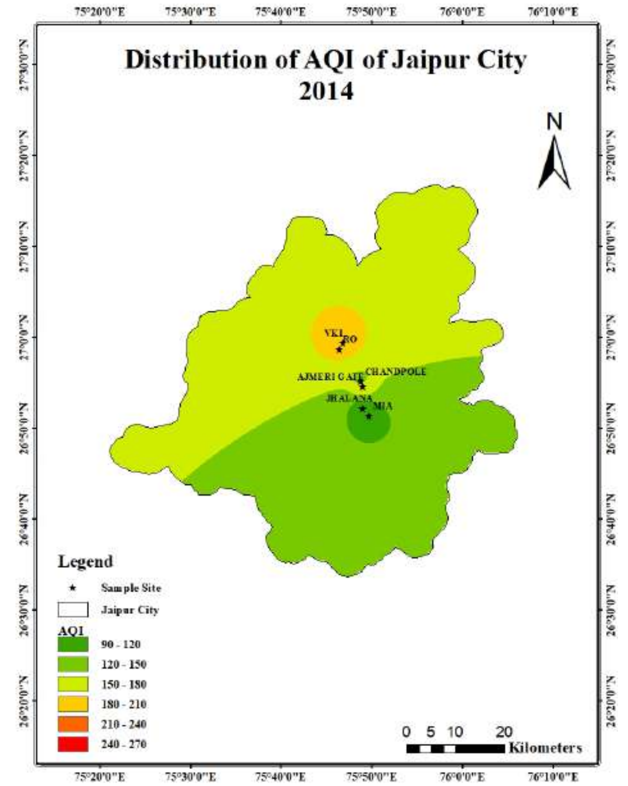
Metropolitan air quality is a critical factor influencing public health and economic productivity. Understanding air quality levels, pollutant concentrations, and associated health risks is essential. Urban air pollution has become increasingly complex due to the multitude and diversity of pollution sources, which significantly impact urban air quality. Indian urban areas typically exceed air quality standards and share similarities in development, infrastructure, industrial activities, and commerce with the study area under examination. Various activities, such as cooking and heating with solid fuels, biomass, kerosene, wood, and fossil fuels in open fires or traditional stoves, contribute to high levels of indoor air pollution.

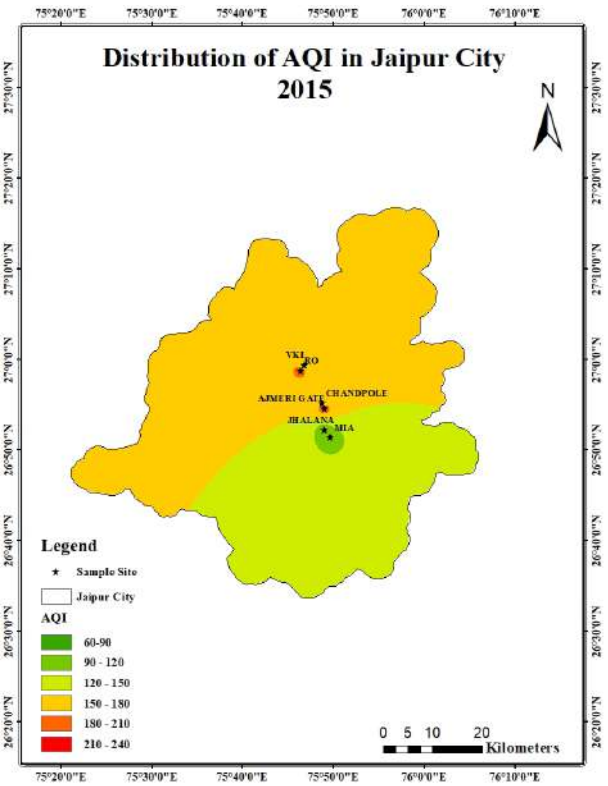
Jaipur, located in northern India, experiences a dry climate and hosts a mix of industrial and commercial activities. The city's ambient air quality is monitored regularly at selected sites across the urban area. This study investigates the spatial and temporal changes in air pollution in Jaipur city from 2011 to 2019. Satellite imagery captured by the LISS 3 satellite was obtained from the NRSC Bhuvan platform for analysis. Interpolation techniques were employed to estimate air pollutant concentrations across the study area. Both Kriging and Inverse Distance Weighted (IDW) methods were utilized for interpolation. IDW differs from Kriging in that it does not involve measurable models or account for spatial autocorrelation. Instead, it uses z-values and distance weights to estimate values in unmeasured areas.

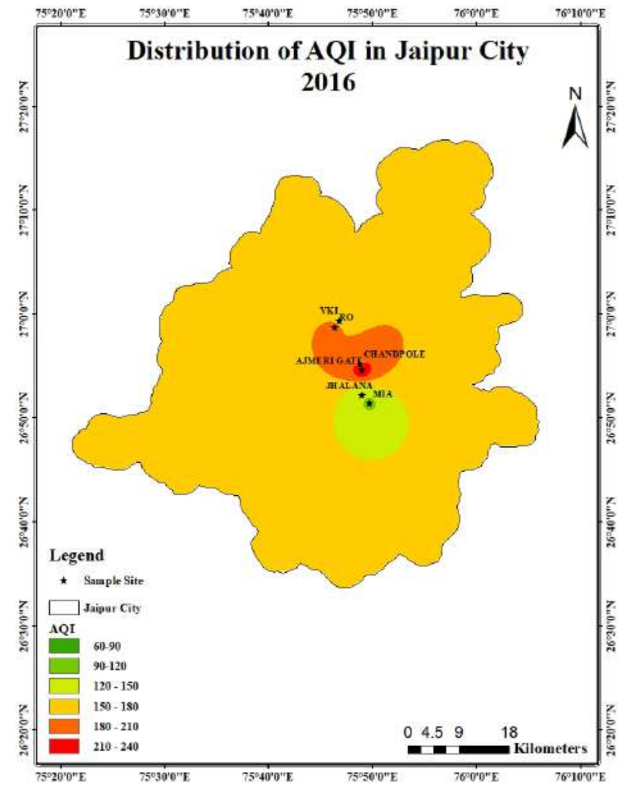





Distribution of AQI in Jaipur City
2013
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
SAMPLE SITE
JAIPUR CITY
AQI
90-120
120-150
150- 180
180 - 210
210 - 240
240 - 270
0 4.25 8.5 17 Kilometers
75°20'0"E
75°30'0"E
75°40'0"E
75°50'0"E
76°0'0"E
76°10'0"E
27°20'0"N
27°10'0"N
27°0'0"N
26°50'0"N
26°40'0"N
26°30'0"N
26°20'0"N


Distribution of AQI of Jaipur City
2014
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
AQI
90 - 120
120 - 150
150 - 180
180 - 210
210 - 240
240 - 270
0 5 10 20 Kilometers
75°20'0"E
75°30'0"E
75°40'0"E
75°50'0"E
76°0'0"E
76°10'0"E
27°30'0"N
27°20'0"N
27°10'0"N
27°0'0"N
26°50'0"N
26°40'0"N
26°30'0"N
26°20'0"N


Distribution of AQI in Jaipur City
2015
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
AQI
60-90
90 - 120
120 - 150
150 - 180
180 - 210
210 - 240
0 5 10 20 Kilometers
75°20'0"E
75°30'0"E
75°40'0"E
75°50'0"E
76°0'0"E
76°10'0"E
27°30'0"N
27°20'0"N
27°10'0"N
27°0'0"N
26°50'0"N
26°40'0"N
26°30'0"N
26°20'0"N


Distribution of AQI in Jaipur City
2016
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
AQI
60-90
90-120
120 - 150
150 - 180
180 - 210
210 - 240
0 4.5 9 18 Kilometers
75°20'0"E
75°30'0"E
75°40'0"E
75°50'0"E
76°0'0"E
76°10'0"E
27°20'0"N
27°10'0"N
27°0'0"N
26°50'0"N
26°40'0"N
26°30'0"N
26°20'0"N

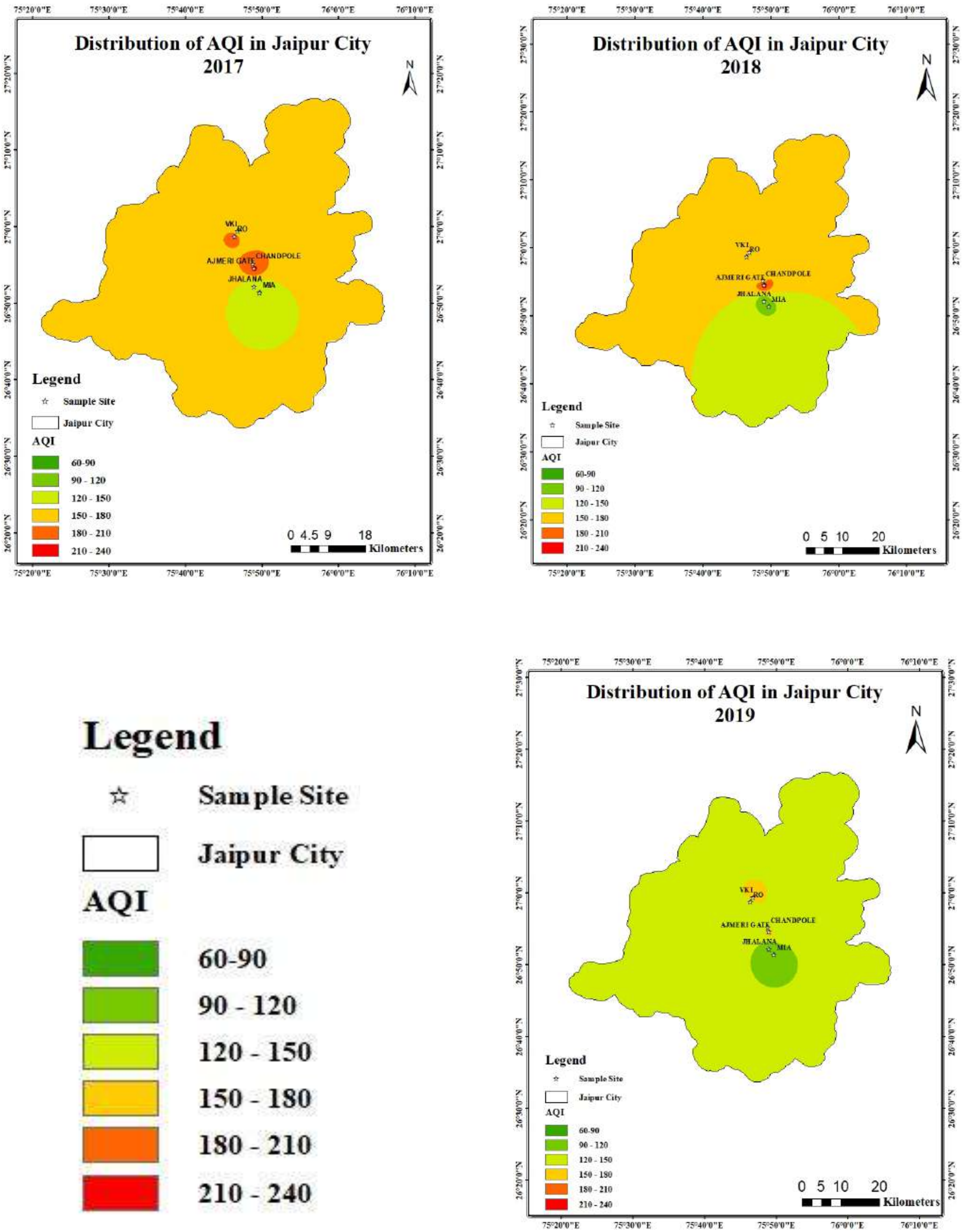


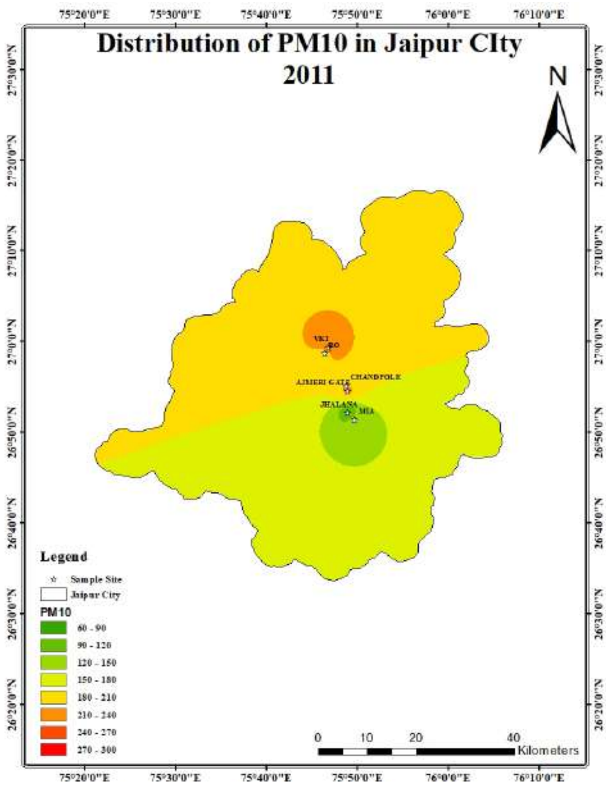
Fig. 3. Air quality index (AQI) in Jaipur city from 2011 to 2019

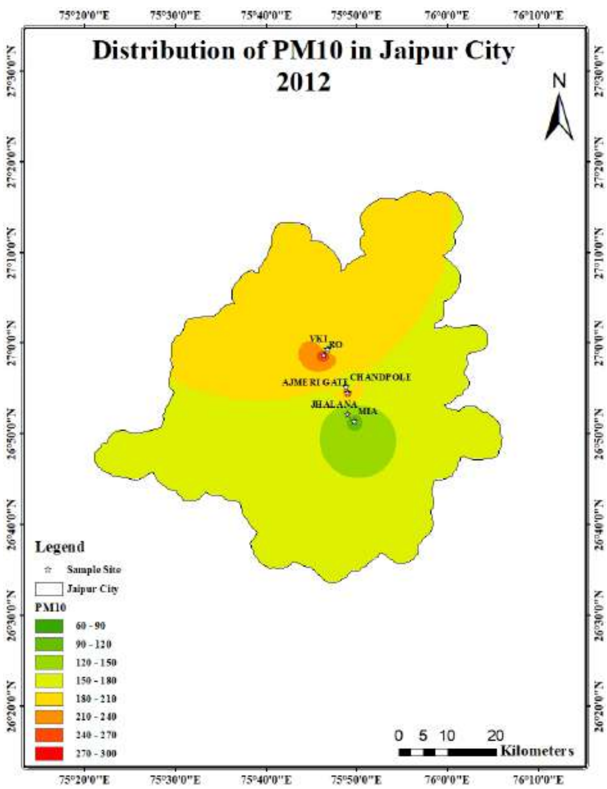
Distribution of AQI in Jaipur city

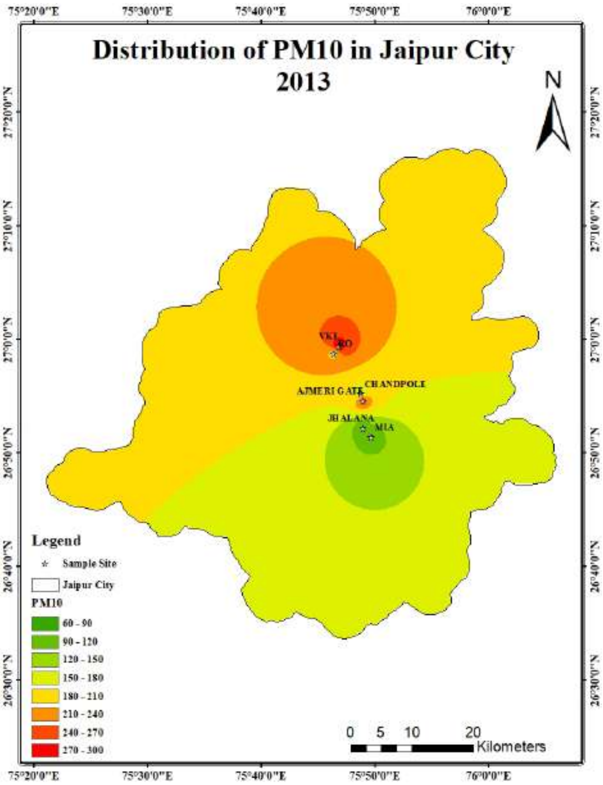
The maps illustrate the distribution of the Air Quality Index (AQI) in Jaipur city from 2011 to 2019, showing consistently high concentrations in the central part of the city. Specifically, four sample sites—Vishwakarma Industrial Area, the Regional Office, Ajmeri Gate, and Chandpole—are located in this area. Air Quality Index (AQI) in Jaipur city from 2011 to 2019 is shown in Fig. 3.

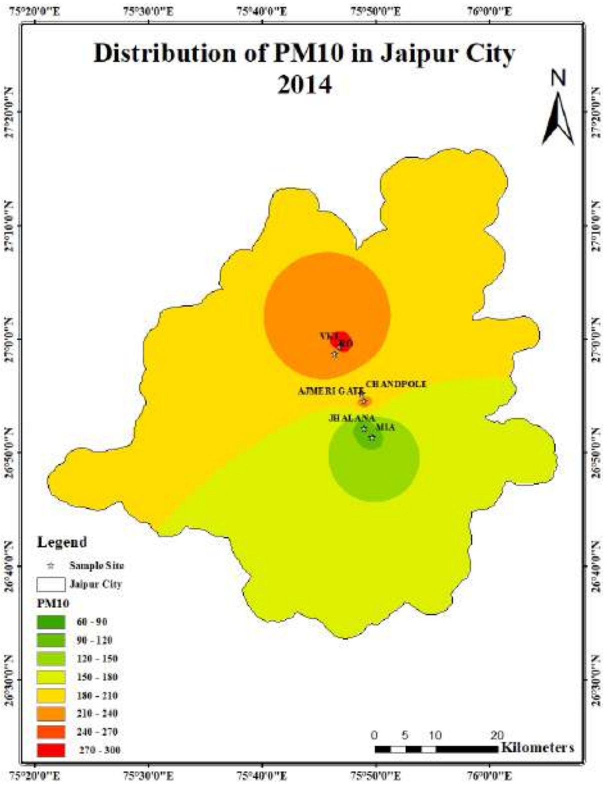
In 2011, the highest AQI concentrations were recorded in Vishwakarma Industrial Area (197) and the Regional Office (161). By 2012, the highest AQI values shifted to the Regional Office (221) and Ajmeri Gate (192). In subsequent years (2013-2014), AQI peaks returned to Vishwakarma Industrial Area and Ajmeri Gate, reaching 245 and 208, respectively, in 2013, and 205 and 190 in 2014. From 2015 to 2017, the highest AQI concentrations persisted in the Regional Office and Ajmeri Gate, with values ranging from 168 to 231. Additionally, a sudden rise in AQI was observed in the Chandpole area in 2016 (202) and 2017 (175).

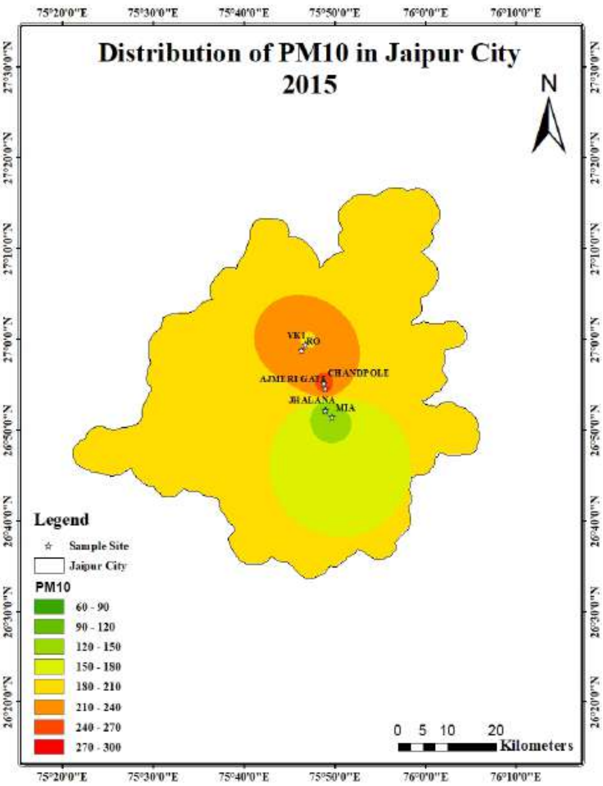
In 2018 and 2019, the highest AQI concentrations were again observed in Vishwakarma Industrial Area, the Regional Office, and Ajmeri Gate, with values varying from 140 to 234. These high concentrations are attributed to industrial activities, commercial operations, and heavy traffic in these areas. Throughout the period from 2011 to 2019, the lowest AQI concentrations were consistently found in Jhalana Doongri and Malaviya Industrial Area. PM_{10} values in Jhalana Doongri ranged from 90 to 120, while in Malaviya Industrial Area; they ranged from 100 to 119. These areas benefit from natural features such as forests (Jhalana Doongri and Nahargarh Forest Reserve) and the hilly terrain of the Aravalli Mountains, resulting in relatively lower AQI concentrations.

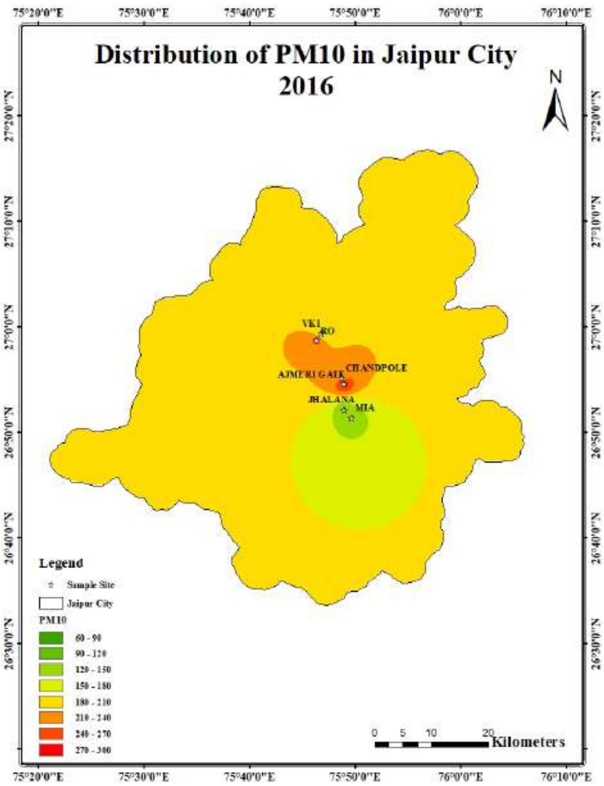





Distribution of PM10 in Jaipur City
2013
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
PM10
60 - 90
90 - 120
120 - 150
150 - 180
180 - 210
210 - 240
240 - 270
270 - 300
0 5 10 20
Kilometers


Distribution of PM10 in Jaipur City
2014
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
PM10
60 - 90
90 - 120
120 - 150
150 - 180
180 - 210
210 - 240
240 - 270
270 - 300
0 5 10 20
Kilometers


Distribution of PM10 in Jaipur City
2015
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
PM10
60 - 90
90 - 120
120 - 150
150 - 180
180 - 210
210 - 240
240 - 270
270 - 300
0 5 10 20
Kilometers


Distribution of PM10 in Jaipur City
2016
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
PM10
0 5 10 20
Kilometers

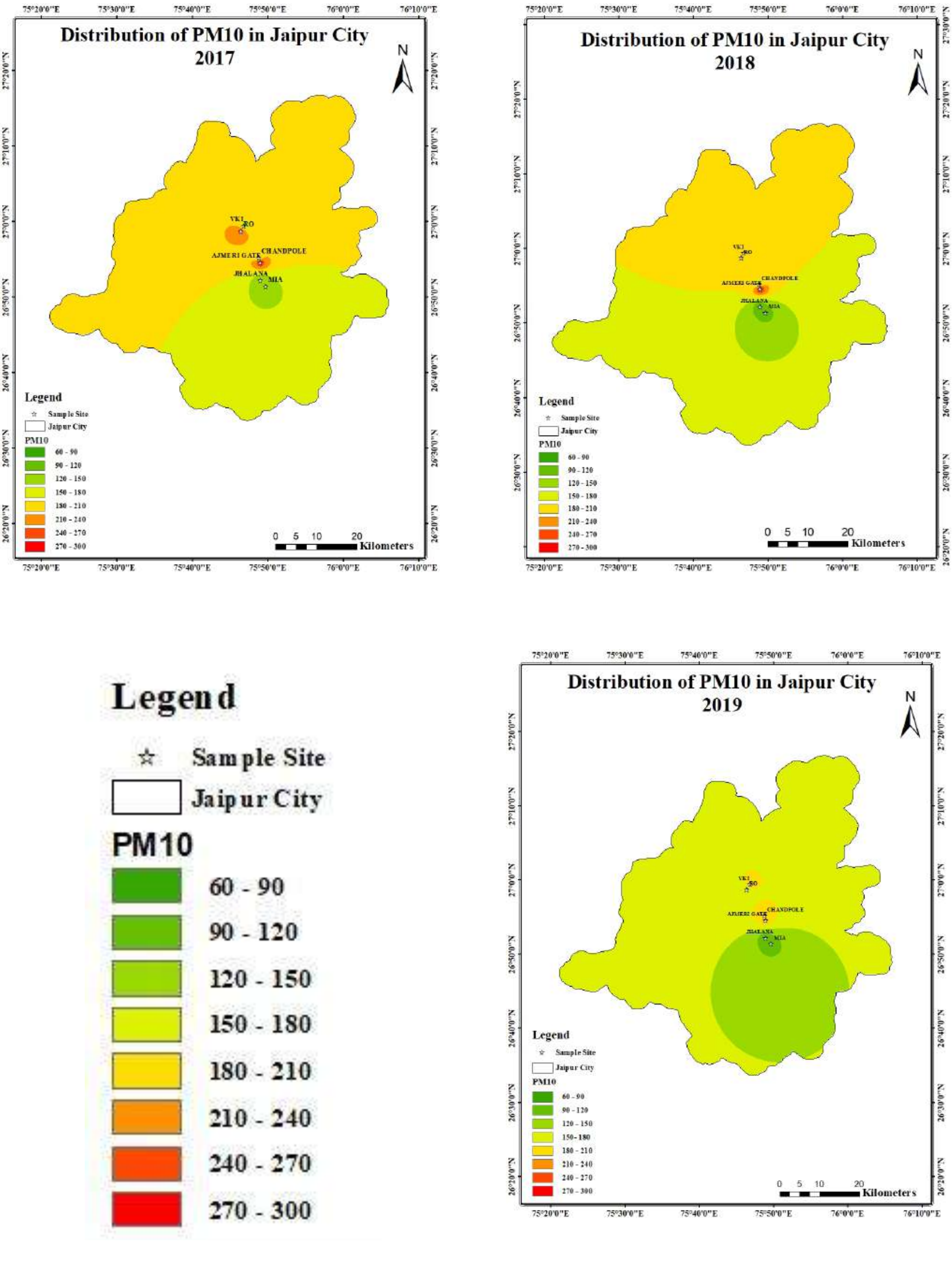
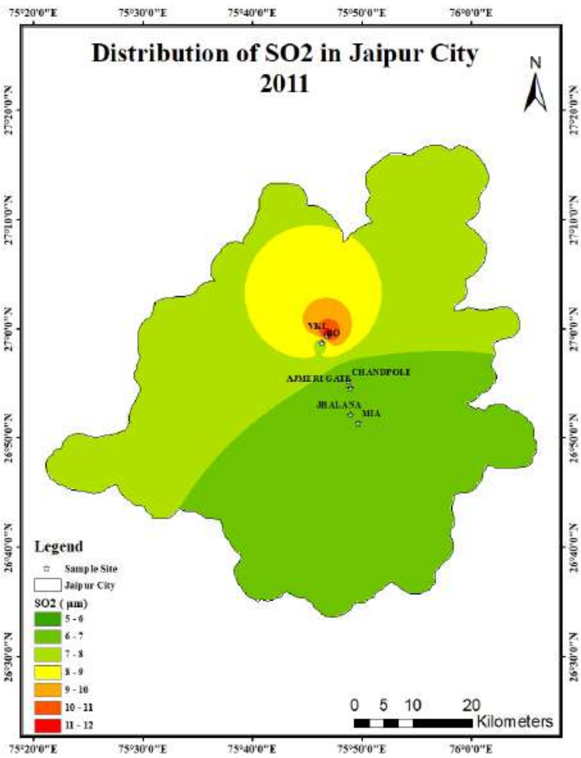


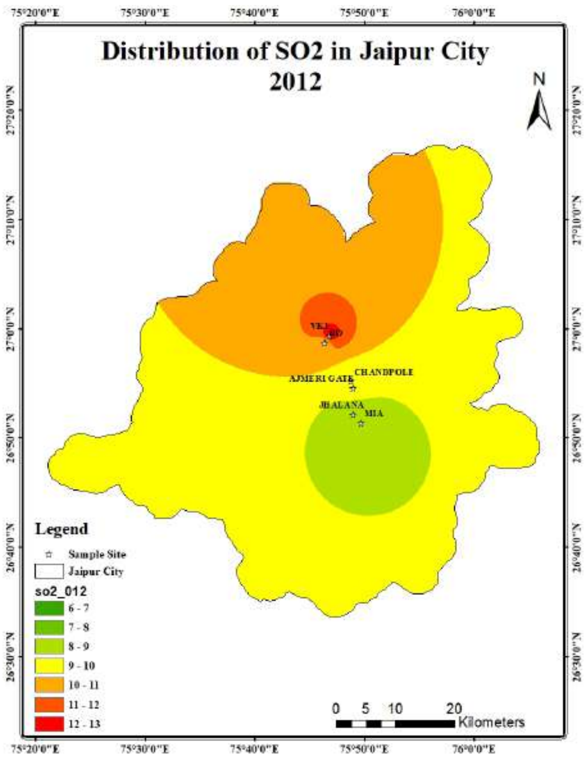
Fig. 4. PM_{10} levels in Jaipur city from 2011 to 2019

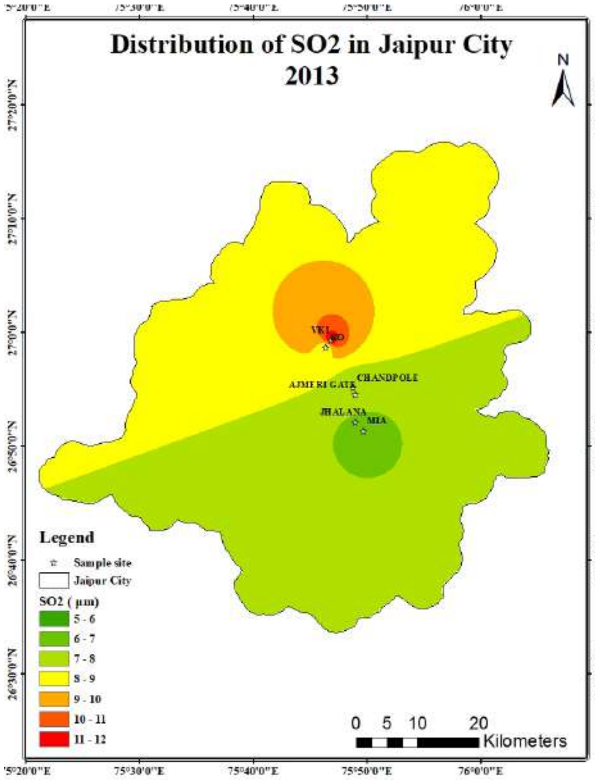
These maps depict the distribution of PM_{10} pollution in Jaipur city from 2011 to 2019, showing significantly high concentrations in the northern and central parts, where four sample sites, Vishwakarma industrial area (VKI), the Regional Office (RO), Ajmeri Gate, and Chandpole are located. The highest PM_{10} concentrations were consistently found in Vishwakarma Industrial Area, Ajmeri Gate, and the Regional Office. Fig. 4 shows the PM_{10} levels in Jaipur city from 2011 to 2019.

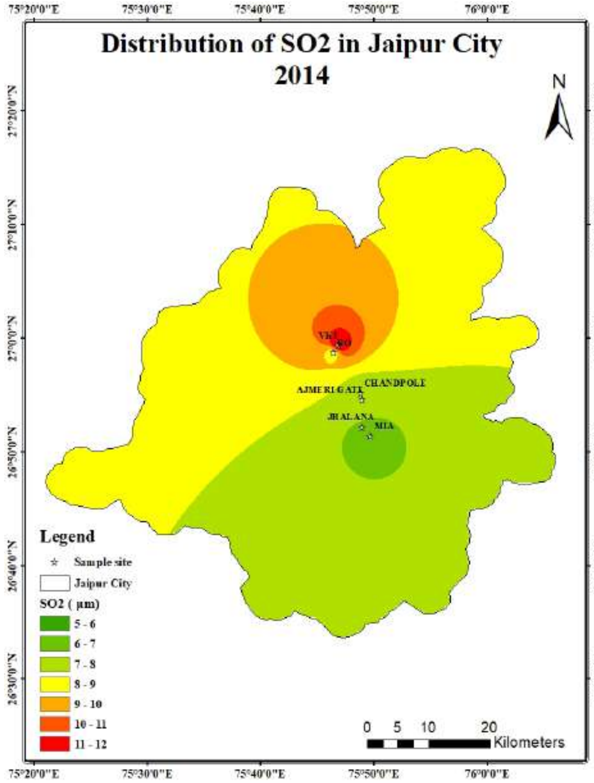
In 2011, PM_{10} levels were 216 µg/m³ at Ajmeri Gate and 246 µg/m³ at Vishwakarma Industrial Area. By 2012, Ajmeri Gate recorded 238 µg/m³, Vishwakarma Industrial Area had 163 µg/m³, and the Regional Office reached 271 µg/m³. In subsequent years, PM_{10} concentrations fluctuated: in 2013, Ajmeri Gate had 258 µg/m³, Vishwakarma industrial area 295 µg/m³, and the Regional Office 197 µg/m³; in 2014, Ajmeri Gate recorded 236 µg/m³, Vishwakarma industrial area 255 µg/m³, and the Regional Office 225 µg/m³; in 2015, Ajmeri Gate had 249 µg/m³, Vishwakarma Industrial Area 201 µg/m³, Chandpole 256 µg/m³, and the Regional Office 230 µg/m³; in 2016, Ajmeri Gate reached 281 µg/m³, Vishwakarma Industrial Area 159 µg/m³, Chandpole 213 µg/m³, and the Regional Office 252 µg/m³. From 2017 to 2019, PM_{10} concentrations remained high, with Ajmeri Gate recording 272 µg/m³, 284 µg/m³, and 193 µg/m³; Vishwakarma Industrial Area with 159 µg/m³, 207 µg/m³, and 207 µg/m³; and the Regional Office with 251 µg/m³, 151 µg/m³, and 202 µg/m³. These areas are characterized by heavy commercial and residential activities, contributing to significant traffic congestion and heightened PM_{10} levels, which exceed the permissible limit of 60 µg/m³.

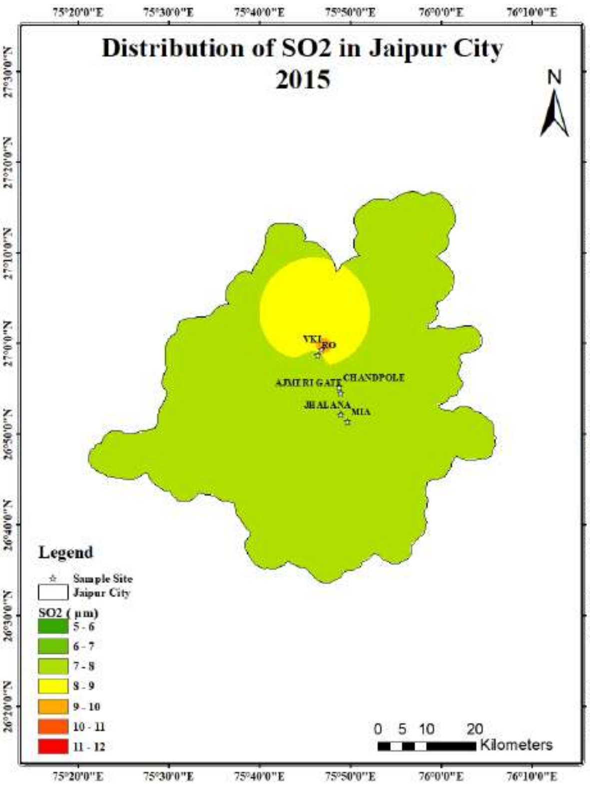
In contrast, the southern parts of Jaipur city showed moderate PM_{10} concentrations, while consistently lower levels were observed in Jhalana Dungri and Malaviya Industrial Area throughout 2011 to 2019. Jhalana Dungri recorded concentrations ranging from 90 µg/m³ to 130 µg/m³, and Malaviya Industrial Area from 103 µg/m³ to 129 µg/m³. These areas benefit from natural features such as forests (Jhalana Dungri and Nahargarh Forest Reserve) and the hills of the Aravalli Mountains, resulting in comparatively lower PM_{10} levels.

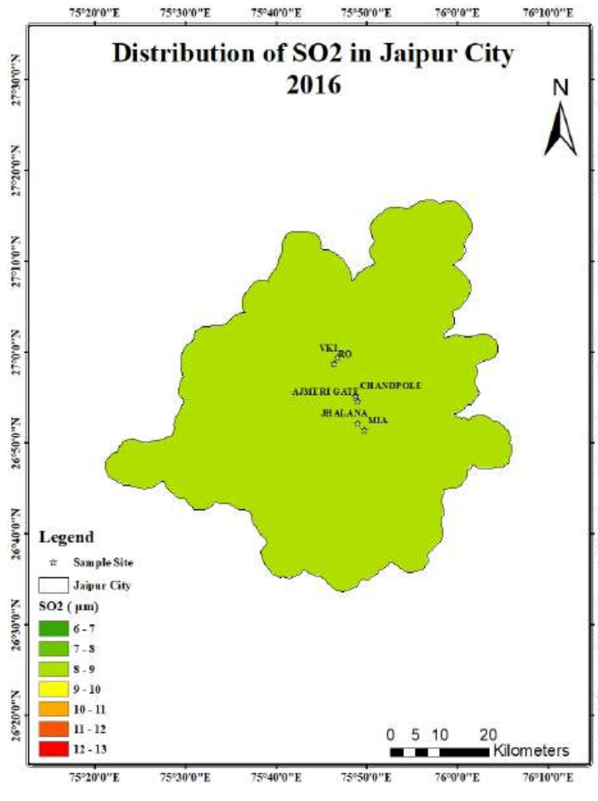





Distribution of SO2 in Jaipur City
2013
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample site
Jaipur City
SO2 (µm)
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
10 - 11
11 - 12
0 5 10 20
Kilometers


Distribution of SO2 in Jaipur City
2014
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample site
Jaipur City
SO2 (µm)
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
10 - 11
11 - 12
0 5 10 20
Kilometers


Distribution of SO2 in Jaipur City
2015
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
SO2 (µm)
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
10 - 11
11 - 12
0 5 10 20
Kilometers


Distribution of SO2 in Jaipur City
2016
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
SO2 (µm)
6 - 7
7 - 8
8 - 9
9 - 10
10 - 11
11 - 12
12 - 13
0 5 10 20
Kilometers

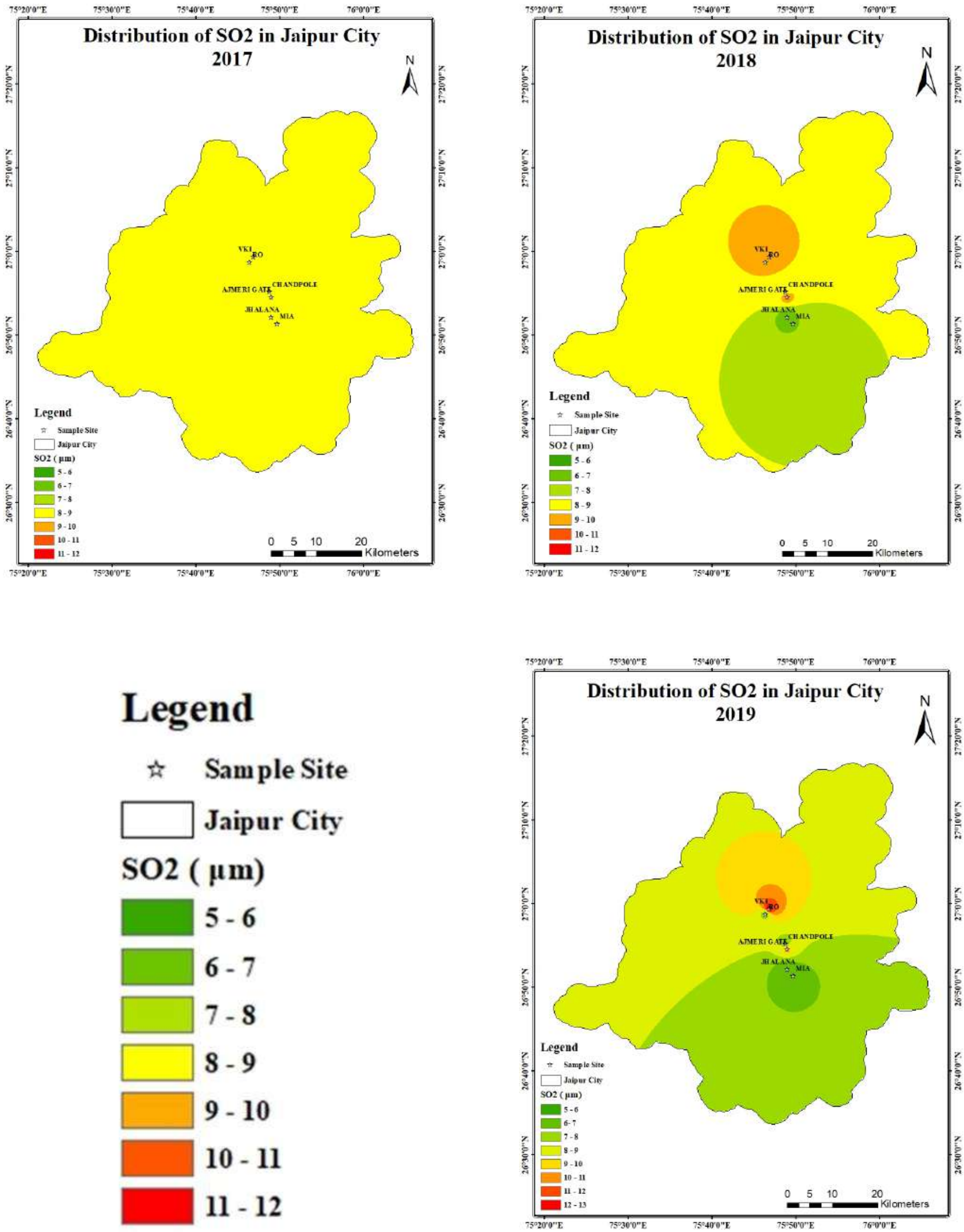
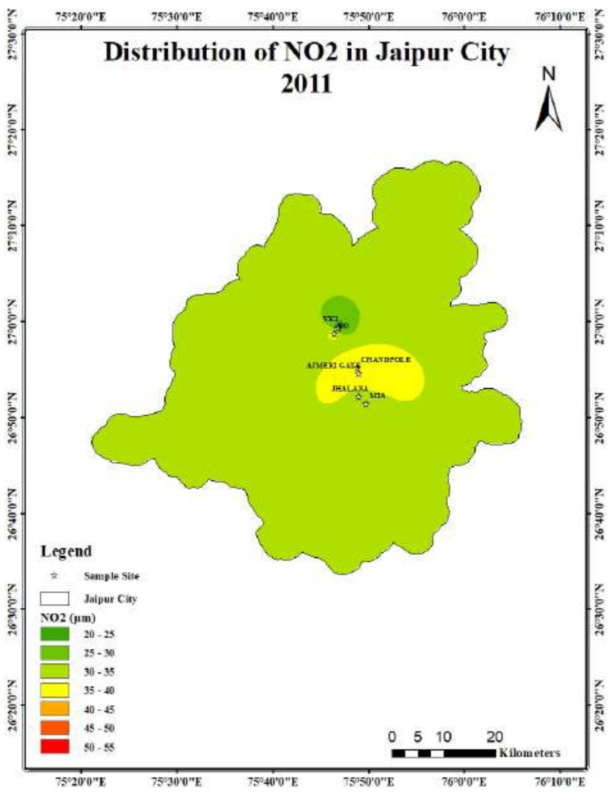
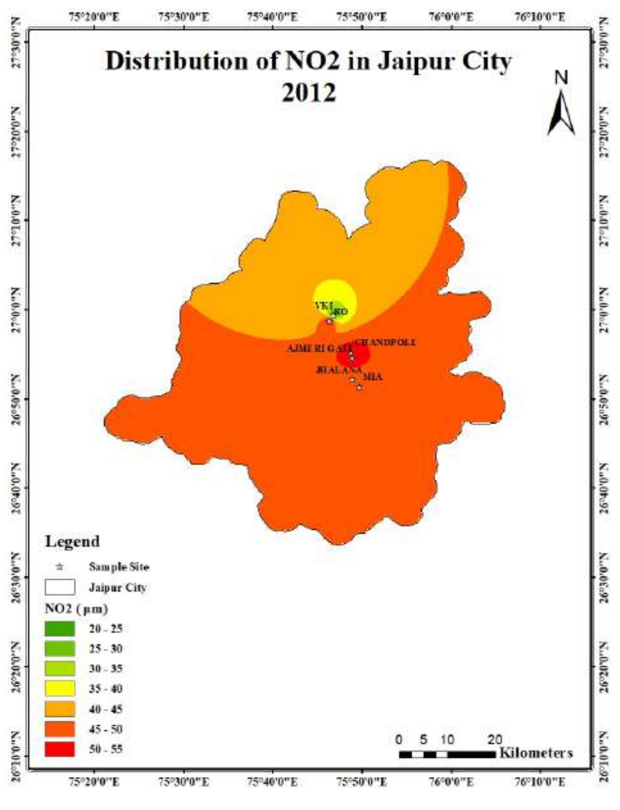


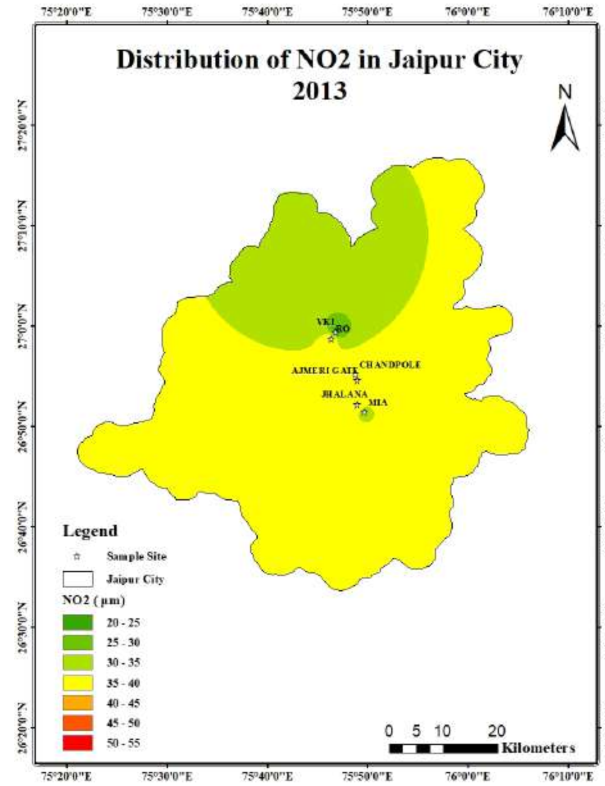
Fig. 5. SO_2 levels in Jaipur city from 2011 to 2019

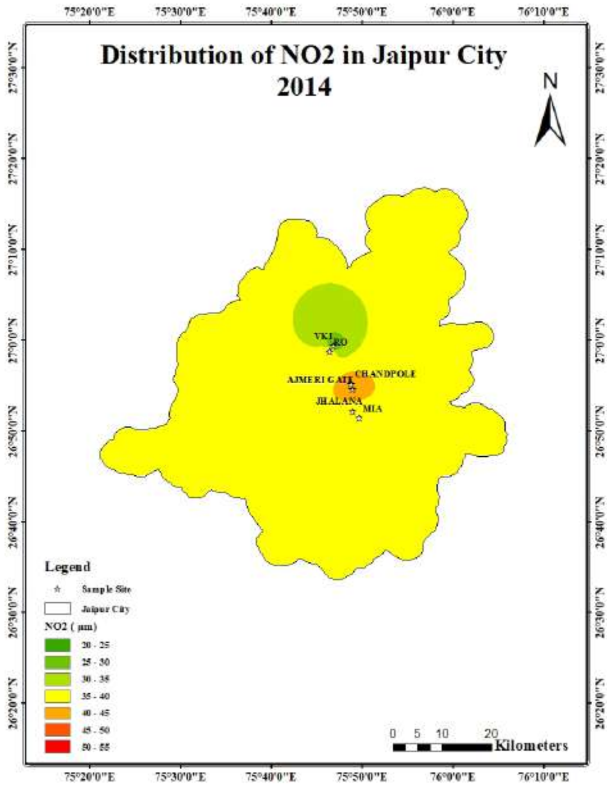
SO_2 pollution is notably high in the northern and central parts of Jaipur city, where four sample sites—Vishwakarma Industrial Area (VKI), the Regional Office (RO), Ajmeri Gate, and Chandpole—are located. Throughout the years, the highest concentrations of SO_2 were consistently observed in Vishwakarma Industrial Area, Ajmeri Gate, Chandpole, and the Regional Office. From 2011 to 2019, SO_2 concentrations in Vishwakarma Industrial Area ranged from 12 μg/m³ to 13 μg/m³, in Chandpole from 6 μg/m³ to 9 μg/m³, in Ajmeri Gate from 6 μg/m³ to 10 μg/m³, and in the Regional Office from 7 μg/m³ to 10 μg/m³. These areas are characterized by heavy industrial and commercial activities, contributing to elevated levels of SO_2 pollution. Fig. 5 shows SO_2 levels in Jaipur city from 2011 to 2019.

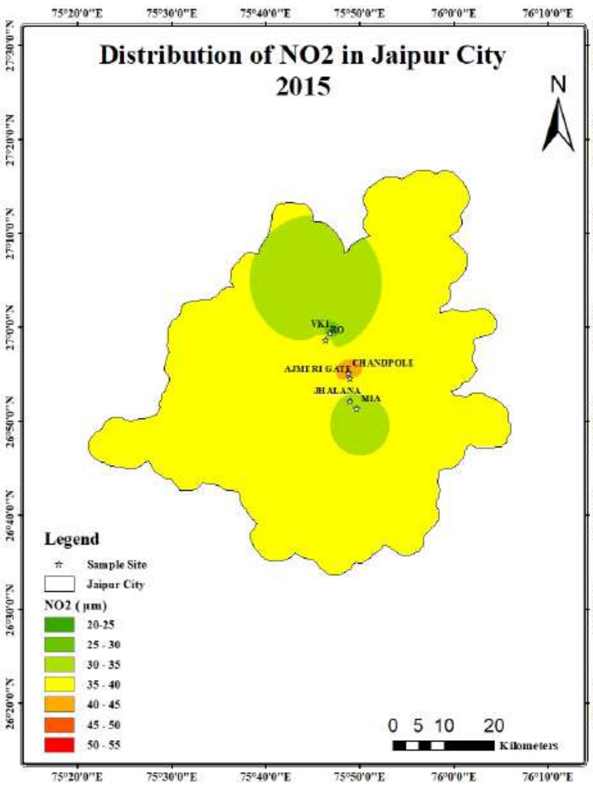
Conversely, the lowest SO_2 concentrations were consistently found in Jhalana Doongri and Malaviya Industrial Area throughout the same period. In Jhalana Doongri, concentrations ranged from 6 μg/m³ to 8 μg/m³, and in Malaviya Industrial Area from 6 μg/m³ to 9 μg/m³. These areas benefit from natural features such as forests (Jhalana Doongri and Nahargarh Forest Reserve) and the hilly terrain of the Aravalli Mountains, resulting in comparatively lower SO_2 levels. The permissible limit for SO_2 is 50 μg/m³, which was not exceeded at any of the sample sites in 2011.

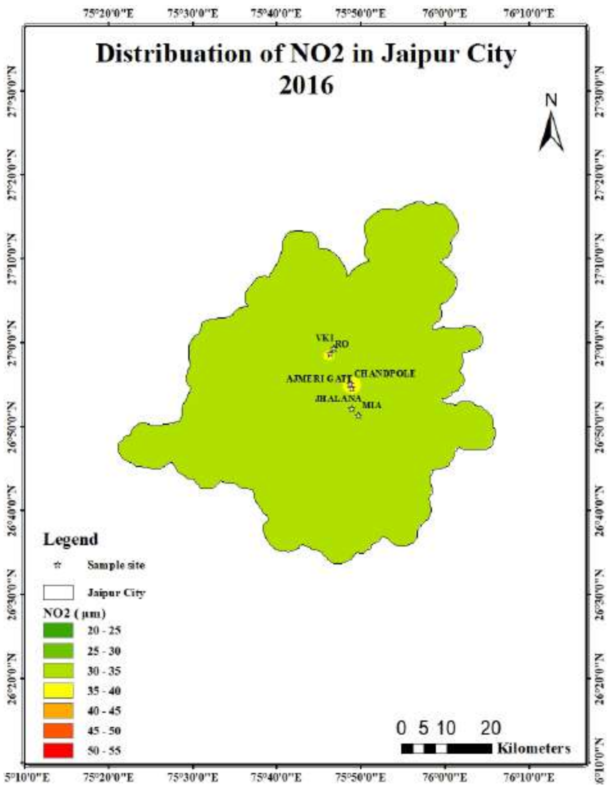





Distribution of NO2 in Jaipur City
2013
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
NO2 (µm)
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
0 5 10 20
Kilometers


Distribution of NO2 in Jaipur City
2014
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
NO2 (µm)
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
0 5 10 20
Kilometers


Distribution of NO2 in Jaipur City
2015
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample Site
Jaipur City
NO2 (µm)
20-25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
0 5 10 20
Kilometers


Distribuation of NO2 in Jaipur City
2016
N
VKI
RO
AJMERI GATE
CHANDPOLE
JHALANA
MIA
Legend
Sample site
Jaipur City
NO2 (µm)
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
0 5 10 20
Kilometers

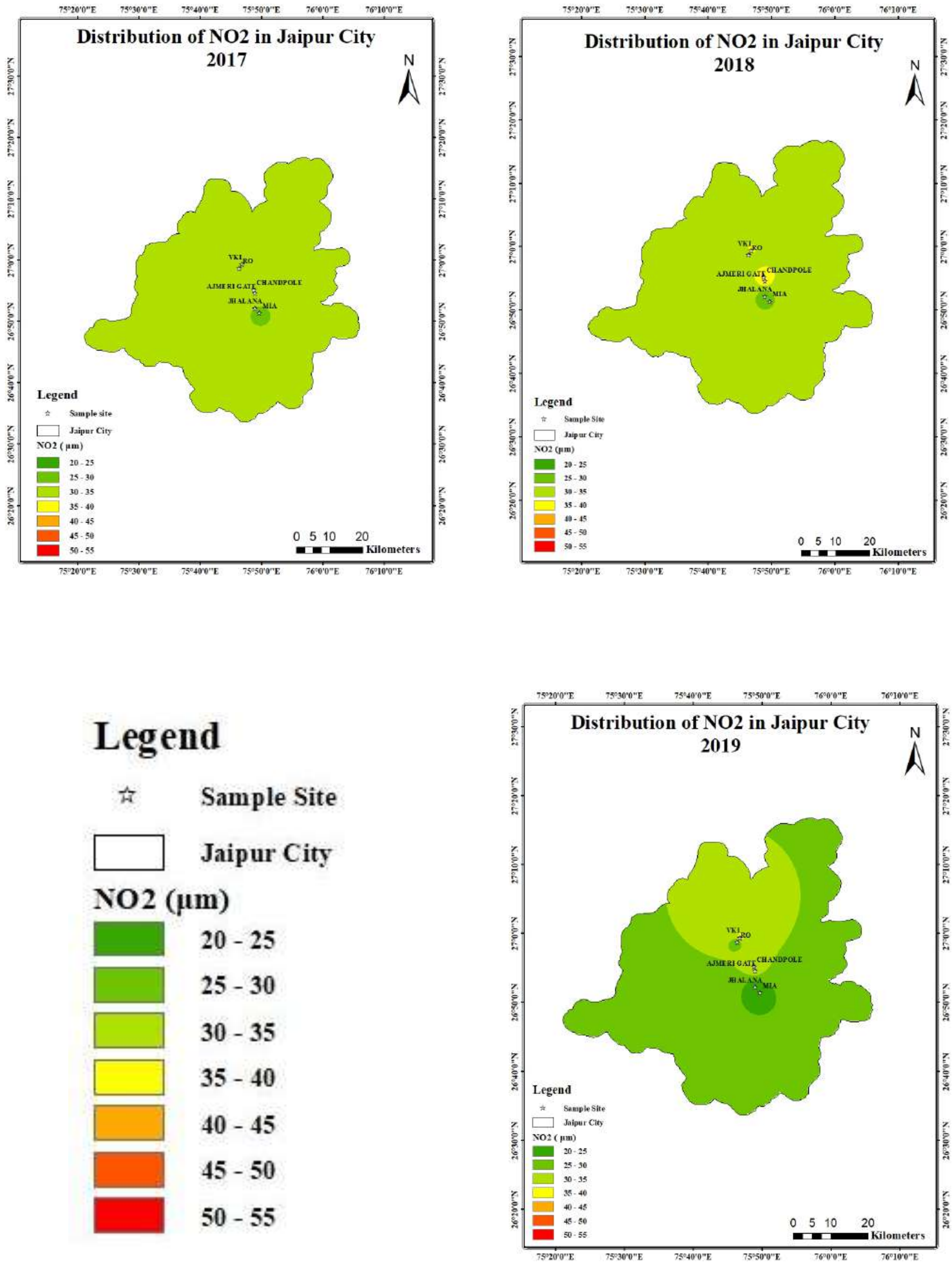


Fig. 6. NO_2 levels in Jaipur city from 2011 to 2019

NO_2 concentrations varied across different areas of Jaipur city from 2011 to 2019. The highest concentrations were observed in Chandpole in 2011 and during 2014-2015, in the Regional Office in 2012-2013 and 2016, and in Ajmeri Gate in 2016-2018. By 2019, the highest NO_2 levels were found in Vishwakarma Industrial Area. Specifically, in Ajmeri Gate, NO_2 concentrations were 38 µg/m³ in 2011, increasing to 53 µg/m³ in 2012, and varying between 31 µg/m³ and 37 µg/m³ from 2013 to 2019. Vishwakarma Industrial Area recorded levels ranging from 21 µg/m³ to 37 µg/m³ over the same period. Chandpole saw concentrations from 39 µg/m³ to 52 µg/m³, while the Regional Office ranged from 27 µg/m³ to 54 µg/m³. Conversely, the lowest NO_2 concentrations were consistently found in Jhalana Doongri and Malaviya Industrial Area throughout these years. In Jhalana Doongri, concentrations ranged from 21 µg/m³ to 46 µg/m³, and in Malaviya Industrial Area from 21 µg/m³ to 47 µg/m³. These areas benefit from natural features and have comparatively lower NO_2 levels due to reduced industrial and traffic activities. Fig. 6 shows NO_2 levels in Jaipur city from 2011 to 2019.

The analysis of air quality in Jaipur from 2011 to 2019 highlights a complex interplay between urban expansion, industrial activities, and environmental factors that significantly impact public health and economic outcomes. The results reveal considerable challenges with air pollution, especially in urban areas where pollution levels frequently surpass national standards. Understanding these dynamics is crucial for developing effective public policies and urban planning strategies to mitigate the health impacts of pollution. The data indicates a distinct contrast in air quality between industrial and natural areas in Jaipur. Regions such as the Vishwakarma Industrial Area and Ajmeri Gate consistently report high Air Quality Index (AQI) values due to emissions from factories, vehicles, and construction. In contrast, residential or commercial areas like Jhalana Doongri area show significantly lower AQI and particulate matter (PM_{10}) levels, benefiting from their natural surroundings. This disparity highlights the need for targeted interventions in the most polluted regions. Throughout the study period, pollutants including PM_{10}, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) displayed troubling trends, with the highest concentrations located in the central and northern parts of the city. PM_{10} levels often exceeded the permissible limit of 60 µg/m³, particularly in the Vishwakarma Industrial Area, where they peaked at 295 µg/m³ in 2013. This ongoing pollution reflects the high level of industrial and commercial activities in these areas, posing serious health risks to local residents. Conversely, the lower pollution levels in Jhalana Doongri area is likely due to natural barriers and vegetation that help filter pollutants. These findings suggest that integrating green spaces into urban planning could significantly improve air quality. Several interconnected factors contribute to the observed air quality trends in Jaipur. Rapid urbanization and population growth have driven increased industrial output and emissions. Traditional practices, such as using solid fuels for cooking and heating in densely populated areas, worsen indoor air pollution. The dependence on fossil fuels for transportation exacerbates urban pollution, with vehicle emissions being a major contributor. Furthermore, inadequate waste management and ongoing construction activities elevate pollution levels, as dust from construction sites worsens air quality. Addressing these challenges requires a comprehensive strategy that incorporates both environmental and socio-economic considerations. The health implications of persistently high pollution levels in Jaipur are severe. Exposure to elevated PM_{10} and other pollutants is linked to various health issues, including respiratory and cardiovascular diseases. Vulnerable populations, particularly children and the elderly, face the greatest risks, highlighting the urgent need for effective public health measures. Continuous monitoring of health outcomes related to air quality is essential for understanding the full impact of pollution on community health. Public awareness campaigns that inform residents about the risks of air pollution and promote healthier behaviors can significantly help reduce health threats. Encouraging the use of cleaner cooking fuels and improving waste disposal methods can greatly decrease both indoor and outdoor pollution levels.

Similar to Jaipur, other World Heritage cities in India, including Chandigarh and Ahmedabad, are facing serious air pollution challenges. In Chandigarh, the pollution statistics present a mixed picture: PM_{10} levels have decreased at industrial sites, but NOx levels are increasing throughout the city. Seasonal changes significantly impact pollutant levels, often resulting in higher concentrations during winter and after the monsoon, primarily due to construction and dust. Although there have been some positive developments, air quality remains a major concern, especially for vulnerable populations experiencing heightened respiratory issues [26, 27]. In Ahmedabad, some areas have shown improvements, with SO_2 and NO_2 levels consistently below national standards. However, there is a concerning rise in Respirable Suspended Particulate Matter (RSPM) and Suspended Particulate Matter (SPM) at specific monitoring stations, largely due to rapid urbanization, population growth, and an increase in vehicles. While efforts to manage certain pollutants have achieved some success, overall air quality still poses health risks, emphasizing the need for ongoing monitoring and intervention [28, 29].

Conclusion

This study provides a comprehensive assessment of pollution levels in Jaipur city, revealing higher concentrations in the northern parts compared to lower levels in the southern areas. These findings were determined using interpolation techniques in ArcGIS 10.4, based on pollution data from various locations. The study found that PM_{10} pollutants formed a predominant cluster with higher concentrations than vapor pollutants. Pollution concentrations varied significantly across different areas due to local activities. The northern part of Jaipur, characterized by industrial establishments, exhibited the highest pollution levels. In the central areas, where commercial and residential activities overlap, pollutants from non-renewable energy sources and heavy traffic contributed to similarly high concentrations. Conversely, pollution levels were notably lower in areas like Jhalana Doongri and the Malaviya Industrial Area (MIA), which can be attributed to ample forest cover and the nature of industries operating there. Historically, the Vishwakarma Industrial Area (VKI) has been one of the most polluted zones in Jaipur due to its concentration of major industries, with pollution levels showing an upward trajectory over the years. The primary air quality concerns in Jaipur revolve around the Air Quality Index (AQI) and PM_{10} levels. SO_2 and NO_2 pollutants were found to be within permissible limits, with NO_2 emissions sourced from activities such as burning fossil fuels, coal, and industrial processes like manufacturing and food processing. SO_2 primarily originates from industrial emissions. Sources of PM_{10} include brickworks, refineries, cement and iron industries, fossil fuel combustion, sandstorms, fires, and certain consumer products.

The study emphasizes the importance of a proactive approach to urban planning and public policy in Jaipur. Policymakers should prioritize environmental sustainability alongside economic growth by implementing stricter regulations on industrial emissions, promoting cleaner technologies, and enhancing public transportation to reduce reliance on private vehicles. Additionally, incorporating green spaces into urban design can enhance air quality and improve residents' overall quality of life. Collaboration among government agencies, industries, and the community is crucial for developing effective policies to address air quality challenges. Ongoing research and data collection will be vital for informing these policies and ensuring that interventions adapt to the changing landscape of urban air pollution.

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Competing interests

No conflicts of interest exist. The study aimed to assess air pollution levels in Jaipur city of India from 2011 to 2019.

Authors' contributions

Mohit Jangir conducted the study under the supervision of Dr. Kheraj and Dr. M.P. Punia.

Mohit Jangir: Contributed to data compilation, interpretation of results, and writing of the research paper.

Parag Jyoti Kashyap: Contributed to data compilation and manuscript preparation.

Sanchali Das Podder: Edited and arranged the writing.

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Ethical considerations

"Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc) have been completely ob-served by the authors."

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