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Seasonal Changes in Air Pollutants and Their Relation to Vegetation over the Megacity Delhi National Capital Region †

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Abstract: Delhi is one of the most densely populated megacities in the world, and it is experiencing deteriorating air quality due to rapid industrialization and excessive use of transportation. The limited emission control measures in Delhi have led to worsening air quality problems, which have become a serious threat to human health and the environment. In the present study, we investigate the long-term (2011–2021) interrelationship between air pollutants and the vegetation index using satellite datasets. Air pollutant data viz. nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were obtained from NASA's Aura satellite called the Ozone Monitoring Instrument (OMI)Additionally, the data for carbon monoxide (CO) and particulate matter 2.5 ($PM_{2.5}$) were obtained from the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) model. The vegetation indices, i.e., the normalized difference vegetation index (NDVI) and the enhanced vegetation oxide (EVI), were collected from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. The analysis of both datasets revealed higher concentrations of air pollutants in the summer months when the NDVI and EVI were minimal. Furthermore, a higher pollution load was observed in the months of October–January when the NDVI and EVI were lower. Furthermore, we also investigated the spatial patterns of $PM_{2.5}$ and other gaseous pollutants (viz. CO, SO_2, and NO_2) and observed that their levels were lower in the vegetated region in comparison to the sparsely vegetated area of Delhi. The present study indicates that vegetation could ameliorate various air pollutants; however, it needs to be validated with ground observed data.

Keywords: air quality; megacity; NDVI; EVI; MODIS; vegetation

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1. Introduction

Urbanization is happening at a rapid pace globally, and Indian cities are no exception to this trend. Urbanization involves the migration of populations from rural to urban areas and the expansion of towns and cities into nearby underdeveloped rural regions. This process brings about significant changes in land use and land cover within a given area. These changes often include the removal of vegetation and soil cover, replacing them with concrete or asphalt surfaces. Additionally, low-rise rural areas are converted into high-rise urban structures, leading to the substitution of agricultural activities in rural regions with industrial and commercial activities in urban areas [1]. As land use patterns rapidly evolve due to urbanization in developing countries, urban sprawl, as it is often referred to, has been associated with pollution, excessive energy consumption, congested roads, and a decline in community and environmental health [2]. The global deterioration of air quality has become a major threat to both human health and the environment due to the effects of urbanization, industrialization, and increased transportation usage. Rapid urbanization in Indian cities not only modifies the urban climate and air quality but also converts agricultural land and green spaces into built-up areas. Urbanization, along with rising population densities, leads to vegetation loss, worsened air quality, and the emergence of urban heat islands. Furthermore, worldwide forest destruction is exacerbated by overexploitation and human activities.

Delhi, the capital of India, is the world's second-most populous and also one of the most polluted metropolitan cities. Over the past few decades, the city has witnessed rapid expansion, both planned and unplanned, at the expense of its green cover due to urbanization [3]. A combination of various factors, including vehicle and industrial emissions, dust, and climatic conditions, has contributed to Delhi's status as the most polluted capital in the world. The air quality in Delhi is particularly affected during the winter months as nearby farmers burn crop residue, and the concurrent Diwali celebration involves the use of fireworks that further degrade the air quality. In order to safeguard human health and protect the environment, it is crucial to urgently reduce air pollution and improve air quality through urban greening efforts. It is widely acknowledged that vegetation plays a key role in trapping air pollutants on leaves, mitigating urban heat islands, and sequestering carbon dioxide, all of which contribute to enhancing air quality. Natural vegetation, such as shrubs and trees, plays a significant role in reducing air pollutants and improving air quality [4]. Vegetation can be used to reduce air pollutant concentrations; however, its application to air pollution control strategies in a mega city like Delhi has become mandatory to observe. Urban green spaces are invaluable resources for cities, as they not only preserve ecological diversity but also provide a range of ecological services. These services include regulating microclimates, reducing noise and air pollution, enhancing rainwater infiltration, and sequestering carbon dioxide [5,6]. Thus, urban green spaces offer multiple benefits, making them vital components of cities in efforts to protect and enhance the environment and the well-being of their inhabitants.

The elimination of air pollutants using green walls and roofs, commonly known as urban green infrastructure (UGI), has previously been the topic of various studies [7]. However, in the context of India, various studies have been conducted, particularly either on vegetation or air pollution, but the studies on the relationships between vegetation and air pollution are very limited. Therefore, the motivation behind this research is to study the relationship between vegetation and air pollution. There is a lack of research work addressing the relationships between vegetation and air pollution over Delhi-NCR using satellite data; therefore, the main aim of this study is the assessment of variations and relations in vegetation indices (e.g., NDVI—normalized difference vegetation index and EVI—enhanced vegetation indices) and air pollutants using satellite data. This study has the potential to contribute knowledge that may help researchers and policymakers to understand the consequences of air pollutants on vegetation, and it can further be used to formulate air pollution control policies.

2. Materials and Methods

2.1. Study Area

The study was carried out over Delhi-NCR (National Capital Region) to evaluate satellite data for vegetation indices and air pollutants. Delhi National Capital Territory (NCRT) is geographically situated between 28.7041° N and 77.1025° E. Geographically, the NCR spans four states—NCT-Delhi, Uttar Pradesh, Haryana, and Rajasthan—with a total of 23 districts. It is situated between 28.4020° N and 76.8260° E [8]. With a total area of 55,038 square kilometers, Delhi-NCR makes up roughly 1.67 percent of India's total land area [9]. Delhi has a humid subtropical climate with long, scorching summers and brief, foggy winters. The annual temperature ranges from 3 degrees Celsius in the winter to 45 degrees Celsius in the summer. Between July and September, during the monsoon season, 400–600 mm of precipitation falls each year [3]. The vegetation found in Delhi is thorny scrub.

2.2. Datasets

The monthly data of the MODIS were used for the NDVI and EVI. These satellite data were downloaded from the GIOVANNI online data system (https://giovanni.gsfc.nasa.gov/giovanni/ accessed on 10 July 2023). These data were created and managed by NASA Goddard Earth Science Data and Information Services Centre (GES DISC). Moreover, the satellite data for SO_2 and NO_2 were obtained from the Ozone Monitoring Instrument (OMI), whereas data for $PM_{2.5}$ and CO were received from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2 model). Based on the differential in the pigments' absorption or reflection properties of near-infrared (NIR) and red (RED) light, NDVI is the most commonly used indicator of vegetation cover. Rouse et al. [10] suggested the use of NDVI as a proxy for vegetation, and researchers frequently use it to calculate leaf area index, green biomass, agricultural productivity, and patterns of vegetation cover change [11,12]. NDVI is the primary indicator of plant health and greenness, and its value always ranges between (−1) and (+1). Dense vegetation is indicated by rising positive NDVI values, and non-vegetated surfaces like barren ground and water are indicated by values that are close to zero or negative [12–14]. In a healthy green leaf, the interior mesophyll structure reflects red light, while chlorophyll and other pigments absorb a significant amount of near-infrared light [12,15,16]. Furthermore, an EVI was created to improve vegetation monitoring by boosting the vegetation signal. It responds more readily to the canopy structure, which includes factors like leaf area index (LAI) and canopy type. EVI is a global vegetation indicator that offers accurate geographical and temporal data on vegetation on a worldwide scale [17].

The satellite data from the MODIS, OMI, and MERRA-2 model will be utilized to analyze the spatiotemporal trend of vegetation and air pollutants in this study. MODIS is an instrument carried by the Terra and Aqua satellites, and readings are taken in the morning and afternoon by the Terra and Aqua satellites, respectively. It contains 36 spectral bands, a resolution of 250 m to 1 km, and its average revisit period is two days [18]. The OMI is a 13 km × 24 km spatially resolved ultraviolet/visible backscatter spectrometer that covers the entire planet in a single day [19]. The OMI monitors trace gases such as formaldehyde (HCHO), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). The analysis of the levels of carbon monoxide (CO) and $PM_{2.5}$ is performed using the most recent edition of global atmospheric reanalysis during the satellite era, known as MERRA-2. The satellite and model data details regarding air pollutants and vegetation indices are given in Table 1.

Table 1. Satellite/model data description of vegetation indices and air pollutants.

Vegetation Indices/ Air Pollutants	Sensors	Data Product Information	Spatial Resolution	Temporal Resolution
NDVI/EVI	MODIS (Terra)	L3–MOD13C2	0.05°	Monthly
SO_2	OMI	L3–OMSO2e	0.25°	Daily
NO_2	OMI	L3–OMNO2d	0.25°	Daily
CO	MERRA-2	M2TMNXCHM	0.5 × 0.625°	Monthly
$PM_{2.5}$	MERRA-2	M2TMNXAER	0.5 × 0.625°	Monthly

3. Result and Discussion

3.1. Seasonal Variations in Vegetation Indices and Different Air Pollutants

This study focuses on assessing the variations in vegetation indices (specifically NDVI and EVI) and four air pollutants (CO, NO_2, $PM_{2.5}$, and SO_2) in the Delhi-NCR region from January 2011 to December 2021 (Figure 1). Both the NDVI and EVI exhibit similar trends throughout the time period, which is expected since they are derived from the same data product (Figure 1a,b). The highest values for NDVI and EVI are observed during the monsoon season (August to September) and spring (February to March), while the lowest values are found in the summer season (May to June) and post-monsoon season

(October to November). The CO levels are at their lowest during the summer months and peak in November (Figure 1c). It is interesting to note the gradual decrease in CO levels during the monsoon season, which aligns with earlier research conducted by Pandey et al. (2017) [20] in the Indo-Gangetic Plains. The concentration of $PM_{2.5}$, a prominent air pollutant, is highest during the summer months (May to June) and the post-monsoon period (November). Conversely, the lowest concentration of $PM_{2.5}$ is observed during the monsoon and spring seasons (Figure 1d) [21]. In the case of the tropospheric column NO_2 (Figure 1e), a peak was observed during the winter month (i.e., December), and its minimum value was observed during the monsoon period (August to September) [22]. On the other hand, regarding the seasonal variations in SO_2, the peak levels occurred during winter (December to January), and minimum levels occurred during the monsoon months (July to September) (Figure 1f).

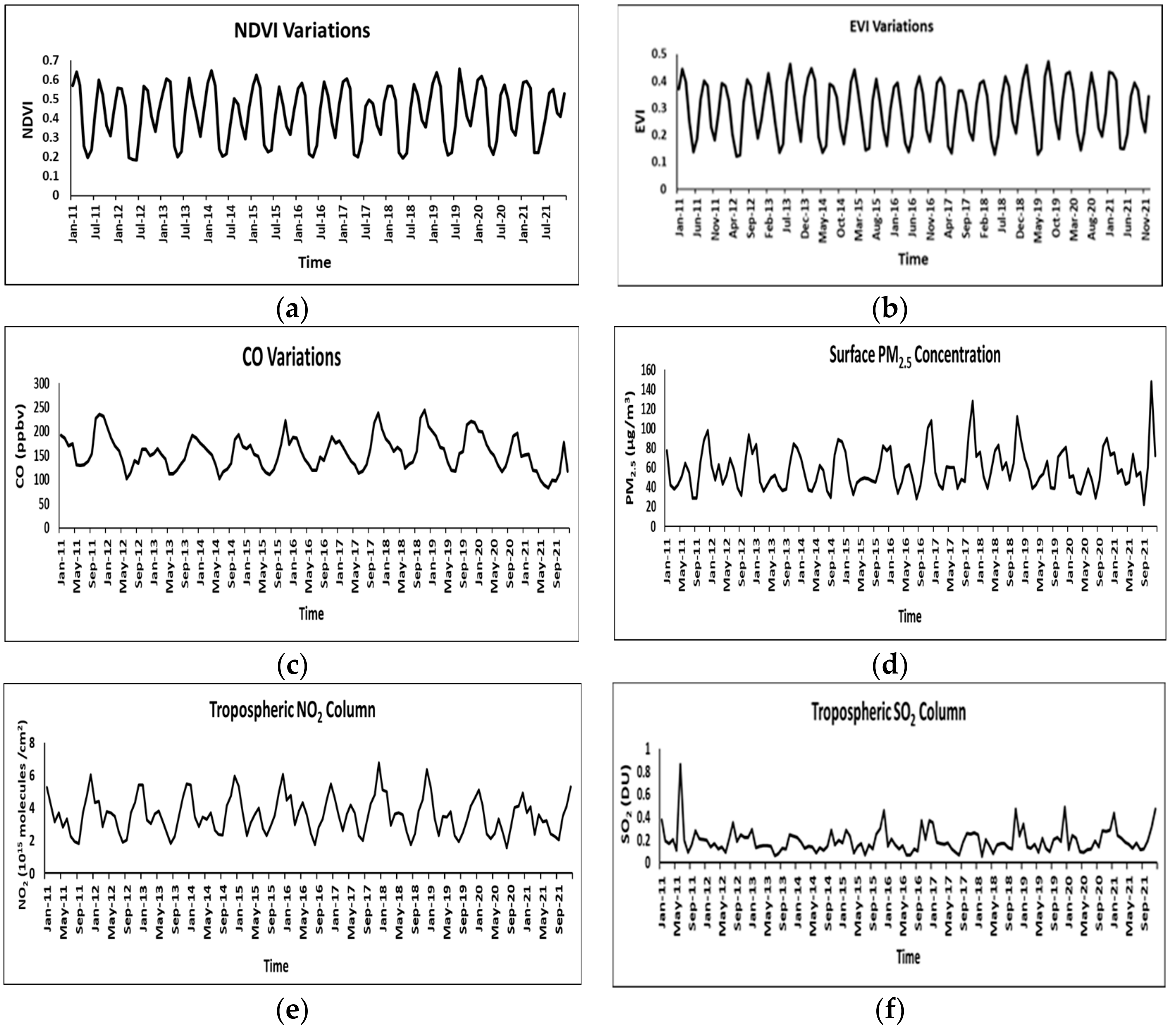

Figure 1. Monthly mean variations in vegetation indices and different air pollutants over Delhi-NCR; (Year January 2011 to December 2021). (**a**) NDVI, (**b**) EVI, (**c**) CO variations, (**d**) surface $PM_{2.5}$ concentration, (**e**) tropospheric NO_2 column, (**f**) tropospheric SO_2 column.

3.2. Comparison of Vegetation Indices with Different Selected Air Pollutants

The mean monthly value of the vegetation indices (NDVI and EVI) was compared with the individual air pollutants viz. SO_2, NO_2, $PM_{2.5}$, and CO (Figure 2). The datasets for eleven years (i.e., January 2011–December 2021) were used to compare trends in the vegetation indices and air pollutants. This study found that the concentration patterns of air pollutants exhibit opposite trends to the vegetation indices, suggesting that vegetation cover influences pollution levels. Specifically, CO, $PM_{2.5}$, NO_2, and SO_2 are consistently higher during the post-monsoon and early winter months (October to December). The winter season is characterized by little rain, which inhibits vegetation development. Therefore, a declined value of NDVI and EVI were observed from November to January. Moreover, cold air, being denser and slower, intensifies air pollution due to its increased density and reduced dispersion [12]. During the post-monsoon season, particularly in October and November, the region experiences minimal vegetation cover. It was observed that the NDVI and EVI values decline around October, coinciding with the autumn season when trees shed their leaves. This leads to a rise in air pollutant levels, as fewer pollutants are absorbed through leaves [23,24]. The reduced vegetation cover during this time is a crucial factor contributing to higher pollutant concentrations.

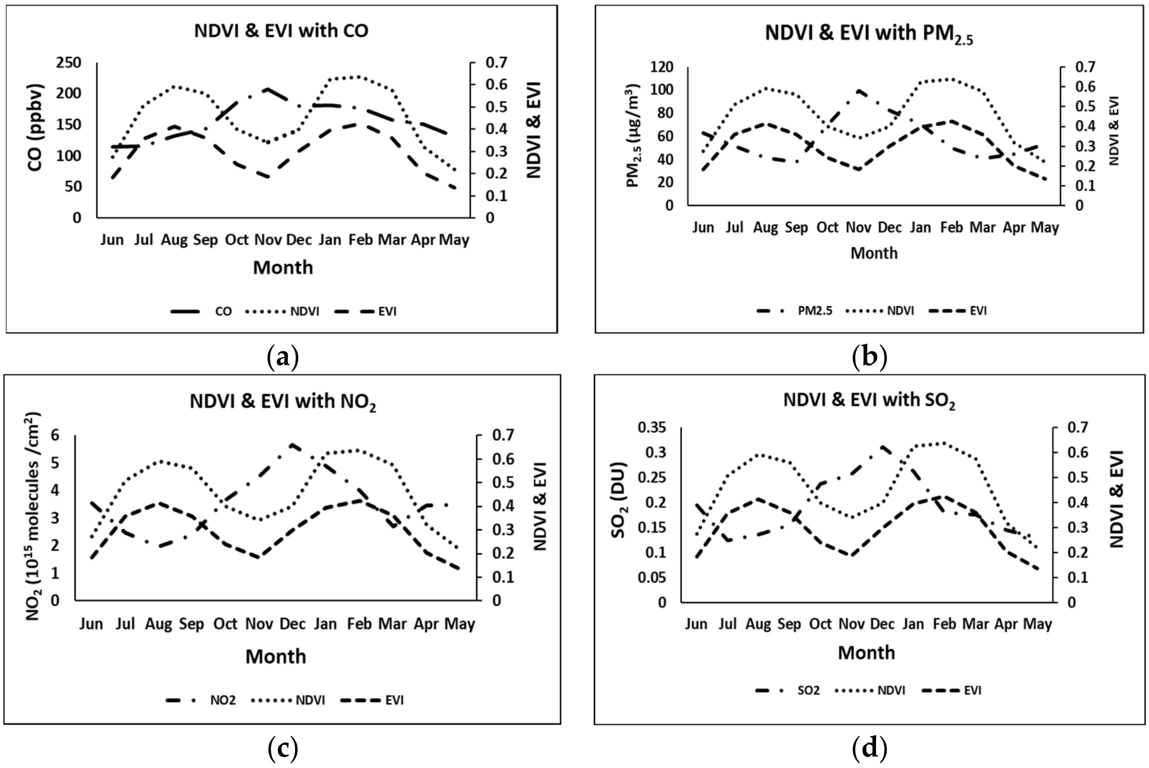

Figure 2. Mean monthly (January 2011 to December 2021) variation and comparison of different air pollutants with the NDVI/EVI of satellite data over Delhi-NCR. (**a**) CO with NDVI and EVI, (**b**) $PM_{2.5}$ with NDVI and EVI, (**c**) NO_2 with NDVI and EVI, (**d**) SO_2 variation with NDVI and EVI.

In contrast, during the spring season (February and March), when new leaves emerge and absorb additional pollutants, NDVI and EVI values increase, resulting in a decrease in air contaminants [17]. Moreover, the monsoon season (July to September) sees an increase in NDVI and EVI values, as plant foliage grows during this period [25]. Rain plays a vital role in washing off air pollutants, leading to decreased pollutant concentrations. On the other hand, hot weather during the summer months (April to June) corresponds to low NDVI and EVI values [24], which contributes to higher pollution levels. Consequently, the NDVI and EVI exhibit inverse relationships with air pollutants [25].

4. Conclusions

This study examines the monthly variations and comparisons between the satellite data of vegetation indices (NDVI and EVI) and air pollutants (CO, NO_2, $PM_{2.5}$, and SO_2). The findings demonstrate that as the vegetation indices increase, air pollutant levels decrease, and vice versa. The values of the indices decrease during the summer and winter seasons but increase during the monsoon season. Conversely, air pollutant concentrations rise during winter and summer but decrease during the monsoon season. Overall, this research suggests that vegetation can play a crucial role in reducing various air pollutants.

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