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Air Pollutant Effect In Ujjain Due To Anthropogenic Activity With Special Reference To Pre And Post Covid

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ABSTRACT
This comprehensive review examines the dynamics of air pollution in Ujjain, Madhya Pradesh, India, with particular emphasis on the periods before, during, and after the COVID-19 pandemic. The unprecedented lockdowns implemented during 2020-2021 created a unique natural experiment that allowed researchers to observe the direct relationship between anthropogenic activities and air quality. This review synthesizes findings from multiple studies, government reports, and air quality monitoring data to present a holistic analysis of how human activities influence air pollution in Ujjain. Results indicate significant reductions in criteria pollutants (PM2.5, PM10, SO2, NO2, CO, and O3) during lockdown periods, with subsequent increases as restrictions eased. The paper examines sector-specific contributions from industries, transportation, construction, and agricultural practices, providing insights into the relative impact of different anthropogenic sources. The temporary improvement in air quality during COVID-19 restrictions offers valuable lessons for developing sustainable pollution control strategies. This review concludes with policy recommendations and identifies research gaps that warrant further investigation to ensure long-term air quality improvement in Ujjain and similar urban centers in developing countries.
Keywords: *Air pollution, COVID-19, lockdown, anthropogenic activities.*

1. INTRODUCTION

1.1 Background on Air Pollution and Public Health

Air pollution represents one of the most significant environmental health risks globally, with the World Health Organization estimating that ambient air pollution causes approximately 4.2 million premature deaths worldwide annually (WHO, 2021). In India, the situation is particularly concerning, with 22 of the world's 30 most polluted cities located within its borders according to the 2020 World Air Quality Report (IQAir, 2021). The deterioration of air quality in Indian urban centers has been linked to rapid industrialization, population growth, increasing vehicular density, construction activities, and energy consumption patterns over recent decades (Balakrishnan et al., 2019). Ujjain, an ancient city in Madhya Pradesh with significant religious and cultural importance, faces similar air quality challenges as other tier-2 cities in India. With a population exceeding 500,000 (Census of India, 2011), Ujjain has experienced substantial urbanization and industrial growth since the early 2000s. The city hosts industries ranging from textiles and pharmaceuticals to food processing units, alongside increasing vehicular traffic and construction activities. These anthropogenic factors collectively contribute to deteriorating air quality, particularly concerning particulate matter (PM2.5 and PM10), nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), and ground-level ozone (O3).

1.2 COVID-19 Pandemic and Lockdown Measures in India

The COVID-19 pandemic, first reported in late 2019, prompted unprecedented lockdown measures globally to contain the viral spread. In India, the government implemented one of the world's strictest nationwide lockdowns beginning March 24, 2020, which was subsequently extended in phases until May 31, 2020, with varying levels of restrictions continuing throughout 2020 and early 2021 (Sharma et al., 2020). These lockdowns led to dramatic reductions in industrial activities, vehicular movement, construction projects, and commercial operations across the country.

For Ujjain specifically, the lockdown phases included:

- Phase 1 (March 24 - April 14, 2020): Complete shutdown of all non-essential services
- Phase 2 (April 15 - May 3, 2020): Continuation with limited relaxations in rural areas
- Phase 3 (May 4 - May 17, 2020): Zone-based relaxations
- Phase 4 (May 18 - May 31, 2020): Further easing of restrictions
- Unlock phases (June 2020 onwards): Gradual resumption of activities

These phased restrictions and subsequent reopening created a unique natural experiment for studying the relationship between anthropogenic activities and air quality parameters.

1.3 Significance of Studying Lockdown Effects on Air Quality

The COVID-19 lockdown periods provided researchers with an unprecedented opportunity to observe how significant reductions in human activities affect air quality parameters over short time frames. This "forced anthropause" (Rutz et al., 2020) allowed for examination of the direct relationship between specific anthropogenic sources and air pollutant concentrations, helping to distinguish between local emissions and regional or transboundary pollution sources.

For a city like Ujjain, where comprehensive source apportionment studies have been limited, the lockdown period offered valuable insights into the relative contributions of various sectors—transport, industry, construction, and domestic activities—to the local air pollution burden. Furthermore, understanding these relationships can inform more targeted and effective pollution control strategies moving forward, particularly as cities aim to balance economic recovery with environmental sustainability in the post-pandemic era.

1.4 Research Objectives and Scope

This review paper aims to comprehensively analyze the impacts of COVID-19 lockdown measures on air quality in Ujjain, with specific objectives to:

1. Assess baseline air pollution levels and trends in Ujjain prior to the COVID-19 pandemic (2018-2019)
2. Analyze changes in key air pollutants (PM2.5, PM10, NO2, SO2, CO, and O3) during different phases of lockdown restrictions (March 2020 - early 2021)
3. Examine the rebound effect in pollution levels during the post-lockdown period (mid-2021 through 2024)
4. Identify major anthropogenic sources contributing to air pollution in Ujjain
5. Compare Ujjain's experience with other similar-sized cities in India and globally
6. Synthesize lessons learned and propose policy recommendations for sustainable air quality management

The scope of this review encompasses air pollution data from government monitoring stations in Ujjain, published scientific literature, reports from pollution control authorities, and comparative studies from other urban centers.

While the primary focus remains on outdoor ambient air quality, indoor air pollution is briefly addressed where relevant to the overall pollution burden.

2. LITERATURE REVIEW

2.1 Global Studies on COVID-19 Lockdown and Air Quality

The unprecedented nature of COVID-19 lockdowns sparked numerous studies examining their effects on air quality worldwide. A comprehensive review by Sokhi et al. (2021) analyzing data from 63 cities across 25 countries found average reductions of 34% for NO_2, 15% for PM2.5, and 9% for O_3 during lockdown periods. These findings demonstrated the global-scale relationship between economic activities and air pollution levels.

In China, where strict lockdown measures were first implemented, studies reported dramatic reductions in pollutant concentrations across major urban centers. Wang et al. (2020) documented NO_2 reductions of up to 53% and PM2.5 reductions of 35% in Beijing during the most restrictive phase of lockdown. Similarly, Huang et al. (2020) reported significantly improved air quality across 44 cities in northern China, with average PM2.5 concentrations decreasing by 14-15 μg/m³ compared to the same period in previous years. European studies highlighted similar trends, though with regional variations. Menut et al. (2020) observed NO_2 reductions of 30-50% across major European cities during lockdown periods, while PM2.5 concentrations showed more variable responses (10-40% reductions) due to the influence of meteorological factors and secondary aerosol formation. Interestingly, several European studies noted increases in ground-level ozone during lockdown periods, attributed to reduced NO_x emissions altering atmospheric chemical equilibria in NO_x-saturated urban environments (Sicard et al., 2020).

2.2 Air Pollution Studies in India During COVID-19

In India, numerous studies have documented significant improvements in air quality during the nationwide lockdown. Sharma et al. (2020) analyzed data from 22 cities across India, reporting average reductions of 43% for PM2.5, 31% for PM10, 18% for CO, and 50% for NO_2 during the initial lockdown phase compared to pre-lockdown periods. Similarly, Mahato et al. (2020) documented improvements in Delhi's air quality with reductions of 60% for NO_2, 39% for PM10, and 52% for PM2.5 during the lockdown. For smaller cities comparable to Ujjain, Kumari and Toshniwal (2020) analyzed air quality data from 12 tier-2 cities in India, finding average reductions of 30-45% in PM2.5 and PM10 concentrations during lockdown periods. Chauhan and Singh (2020) specifically studied 10 cities across India, noting that smaller industrial cities showed greater relative improvements in air quality compared to megacities, suggesting that local emission sources played a dominant role in their pre-pandemic pollution profiles.

Studies from neighboring cities in Madhya Pradesh provide contextual reference for Ujjain. Research by Sharma et al. (2021) documented reductions of 38% in PM10, 42% in PM2.5, and 51% in NO_2 in Indore during the initial lockdown phase. Similarly, Gupta et al. (2021) reported significant improvements in Bhopal's air quality, with PM2.5 concentrations decreasing by 46% compared to pre-lockdown levels.

2.3 Source Apportionment Studies in Indian Urban Centres

Understanding the contribution of different sources to ambient air pollution is essential for developing targeted control strategies. Comprehensive source apportionment studies from major Indian cities provide valuable reference points for interpreting Ujjain's situation. Research by CPCB (2022) across 16 Indian cities identified vehicular emissions (20-35%), industrial activities (15-30%), dust from construction and road surfaces (20-25%), biomass burning (10-15%), and domestic fuel use (6-10%) as the primary contributors to PM2.5 pollution. For Madhya Pradesh specifically, a source apportionment study by Sharma et al. (2023) in Indore identified vehicular emissions as the dominant source of PM2.5 (32%), followed by industrial emissions (24%), dust (18%), biomass burning (14%), and secondary aerosols (12%). Similar patterns have been observed in Bhopal, with vehicular and industrial contributions accounting for over 50% of PM2.5 concentrations (MPPCB, 2022).

For Ujjain specifically, comprehensive source apportionment studies are limited. However, preliminary assessments by MPPCB (2021) suggest that vehicular emissions, industrial activities (particularly from textile units and pharmaceutical manufacturing), construction dust, and seasonal agricultural burning are significant contributors to the city's pollution load.

2.4 Recovery Patterns in Post-Lockdown Periods

As lockdown restrictions eased globally, researchers observed varying patterns of pollution rebound. Studies from China indicated rapid returns to pre-pandemic pollution levels following the resumption of economic activities. For example, Wang and Su (2020) documented that air quality in Beijing and other major Chinese cities had nearly returned to pre-pandemic levels by June 2020, just months after the most stringent restrictions were lifted. In Europe, Gkatzelis et al. (2021) observed more gradual returns to baseline pollution levels, with air quality in many cities remaining improved compared to pre-pandemic averages even months after lockdown measures were eased. This suggested potential long-term changes in work patterns, transportation habits, and industrial operations influencing emission patterns. Indian studies documented varied recovery trajectories across different cities and pollutants. Ravindra et al. (2021) analyzed six major Indian cities, finding that PM2.5 and PM10 levels rebounded to 70-90% of pre-lockdown concentrations within two months of restrictions being eased, while NO2 concentrations recovered more slowly, reaching only 60-75% of baseline levels by the end of 2020. These patterns suggested differential recovery rates across economic sectors, with industrial and construction activities resuming more rapidly than transportation reaching pre-pandemic levels.

3. AIR POLLUTION TRENDS IN UJJAIN

3.1 Pre-COVID Air Quality Status (2018-2019)

Prior to the COVID-19 pandemic, Ujjain, like many mid-sized Indian cities, experienced concerning levels of air pollution, particularly during winter months. Data from the continuous ambient air quality monitoring station (CAAQMS) operated by the Madhya Pradesh Pollution Control Board (MPPCB) at Mahakal Temple Area revealed that during 2018-2019, the city frequently exceeded the National Ambient Air Quality Standards (NAAQS) for particulate matter. Analysis of pre-COVID monitoring data (2018-2019) shows that average PM10 concentrations in Ujjain typically ranged from 80-120 μg/m³ during summer months and 120-180 μg/m³ during winter months, consistently exceeding the NAAQS annual standard of 60 μg/m³ (MPPCB, 2020). Similarly, PM2.5 concentrations averaged 45-70 μg/m³ during summer and 70-110 μg/m³ during winter, significantly higher than the annual standard of 40 μg/m³.

Gaseous pollutants showed seasonal variability but generally remained within acceptable limits. Average NO2 concentrations ranged from 25-35 μg/m³, occasionally spiking to 40-50 μg/m³ during peak traffic hours. SO2 concentrations typically remained below 20 μg/m³, reflecting the limited presence of heavy industries using sulfurrich fuels in the immediate vicinity. CO concentrations averaged 0.8-1.5 mg/m³, with higher values observed during morning and evening rush hours (MPPCB, 2020). The Air Quality Index (AQI) for Ujjain during this period predominantly fell in the "Moderate" (101-200) to "Poor" (201-300) categories, with occasional days reaching the "Very Poor" (301-400) category during winter months when meteorological conditions favored pollutant accumulation. The city experienced approximately 45-60 days annually with AQI exceeding 200, primarily during October-February when temperature inversions, lower mixing heights, and increased biomass burning for heating contributed to pollution accumulation (CPCB, 2019).

3.2 Air Quality During COVID-19 Lockdown Phases (2020-2021)

The implementation of COVID-19 lockdown measures in March 2020 led to dramatic improvements in Ujjain's air quality. During the initial complete lockdown phase (Phase 1: March 24 - April 14, 2020), monitoring data revealed unprecedented reductions in all criteria pollutants:

- PM10 concentrations decreased by 52-58%, averaging 45-55 µg/m³
- PM2.5 concentrations fell by 48-55%, averaging 20-30 µg/m³
- NO2 showed the most dramatic reduction of 65-70%, reflecting the near-complete cessation of vehicular movement
- SO2 concentrations decreased by 30-35%
- CO levels dropped by 40-45%
- Ground-level ozone showed variable patterns, with slight increases (5-10%) observed in some areas, consistent with the NOx-limited atmospheric chemistry in smaller cities (MPPCB, 2021)

Analysis of AQI values during this period showed that Ujjain's air quality predominantly remained in the "Good" (0-50) to "Satisfactory" (51-100) categories, representing a significant deviation from typical seasonal patterns. The city experienced zero days with AQI exceeding 200 during the strictest lockdown phase (Patel et al., 2021).

During subsequent lockdown phases with gradual relaxations (May-June 2020), air quality parameters showed incremental increases but remained significantly improved compared to pre-pandemic levels:

- Phase 2-3 (April 15 - May 17, 2020): Pollutant concentrations remained 40-50% below pre-pandemic levels
- Phase 4 and early Unlock phases (May 18 - July 2020): Pollutant concentrations gradually increased but remained 30-40% below pre-pandemic levels

A detailed temporal analysis by Sharma et al. (2021) using satellite observations and ground monitoring data revealed that the air quality improvements in Ujjain during lockdown correlated strongly with mobility data, with the most significant improvements observed in areas with normally high traffic density.

3.3 Air Quality During Partial Restrictions (Mid-2021)

As restrictions eased and economic activities gradually resumed in late 2020 and early 2021, Ujjain's air quality began showing signs of deterioration. However, during this transition period with partial restrictions still in place, pollution levels remained below pre-pandemic averages:

- During November 2020-February 2021 (typically the most polluted months), PM10 concentrations averaged 90-130 µg/m³, approximately 25-30% lower than the same period in 2019-2020
- PM2.5 levels during this period averaged 50-80 µg/m³, approximately 20-25% lower than pre-pandemic winters

- NO_2 concentrations showed a slower recovery rate, averaging 22-30 μg/m³, still 15-20% below pre-pandemic levels
- CO concentrations returned to approximately 85-90% of pre-pandemic levels

The gradual return of pollution levels correlated closely with phased resumption of economic activities, with industrial emissions recovering more rapidly than transportation-related emissions. This pattern aligns with broader national trends observed across Indian cities during this period (CPCB, 2022).

3.4 Post-COVID Recovery and Current Trends (2022-2024)

By mid-2022, as most pandemic-related restrictions were lifted and economic activities fully resumed, Ujjain's air quality parameters largely returned to pre-pandemic levels, with some notable variations:

- PM10 and PM2.5 concentrations by late 2022 had returned to approximately 90-95% of pre-pandemic levels, suggesting that the predominant sources of particulate pollution had largely resumed operations
- NO_2 concentrations stabilized at approximately 85-90% of pre-pandemic levels, potentially reflecting lasting changes in work patterns and transportation habits
- SO_2 and CO levels returned to pre-pandemic averages by early 2023

Interestingly, analysis of 2023-2024 data reveals that while peak pollution levels during adverse meteorological conditions have returned to pre-pandemic patterns, average pollution levels across seasons remain slightly below pre-2020 benchmarks. This could indicate subtle but lasting changes in emission patterns or increased adoption of cleaner technologies accelerated by pandemic-induced economic restructuring (MPPCB, 2024). A study by Gupta et al. (2023) analyzing three years of post-lockdown data across mid-sized cities in central India found that cities like Ujjain exhibited a "new normal" baseline approximately 5-10% below pre-pandemic levels for most pollutants. This pattern was attributed to several factors including:

- Accelerated adoption of work-from-home policies reducing daily commute traffic
- Increased digitalization of services reducing unnecessary travel
- Greater awareness and implementation of air pollution control measures
- Economic restructuring with some high-polluting industries not resuming full operations

3.5 Comparative Analysis with Other Cities

Comparing Ujjain's experience with other similar-sized cities provides valuable context for understanding the specific impact of anthropogenic factors on local air quality. Analysis of data from cities with comparable population and economic profiles reveals interesting patterns:

In comparison to Indore (the largest city in Madhya Pradesh), Ujjain experienced more significant relative improvements during lockdown periods (52-58% reduction in PM10 vs. 38% in Indore), suggesting a higher contribution of local sources to Ujjain's pollution burden. Conversely, Indore's pollution levels rebounded more rapidly during the recovery phase, reaching pre-pandemic levels by early 2022, while Ujjain maintained slightly improved air quality through mid-2022 (Sharma et al., 2023). When compared to Ratlam, another religious-cultural city in Madhya Pradesh with similar population size, Ujjain showed comparable patterns of pollution reduction during lockdown (50-55% reduction in particulate matter) but experienced a faster rebound during the recovery phase. This difference has been attributed to Ujjain's more diverse economic base and higher religious tourism, which resumed more rapidly following easing of restrictions (MPPCB, 2023). Comparing with Kota

(Rajasthan), an industrial city of similar size, reveals that industrial contributions to pollution loads differ significantly. Kota showed less dramatic improvements during lockdown (30-35% reduction in PM10) and more rapid returns to baseline levels, reflecting its heavier industrial footprint compared to Ujjain's more mixed emission profile (Sharma and Kumar, 2022).

4. SOURCES AND CAUSES OF AIR POLLUTION IN UJJAIN

4.1 Industrial Emissions

Industrial activities represent a significant contributor to Ujjain's air pollution burden, though the city lacks the heavy industrial presence characteristic of major manufacturing hubs. According to the MPPCB industrial inventory (2022), Ujjain hosts approximately 450 industrial units, predominantly in the small and medium-scale categories. The primary industrial sectors include:

- Textile manufacturing and processing units (approximately 120 units)
- Pharmaceutical manufacturing (approximately 40 units)
- Food processing industries (approximately 80 units)
- Engineering and metal fabrication workshops (approximately 60 units)
- Chemical manufacturing (approximately 30 units)
- Other miscellaneous industries (approximately 120 units)

Analysis of emission patterns during lockdown periods provides insight into the industrial contribution to various pollutants. Based on comparative studies by Patel et al. (2021), industrial sources are estimated to contribute:

- 20-25% of PM10 emissions in Ujjain
- 15-20% of PM2.5 emissions
- 25-30% of SO2 emissions
- 15-20% of NOx emissions

The textile sector represents a particularly significant source, with processes including spinning, weaving, dyeing, and printing generating particulate matter and volatile organic compounds (VOCs). An emissions inventory study by MPPCB (2023) estimated that textile units contribute approximately 30-35% of industrial PM2.5 emissions in Ujjain. The pharmaceutical manufacturing sector, while smaller in number, contributes significantly to Ujjain's industrial emissions, particularly VOCs and hazardous air pollutants (HAPs). Studies suggest that pharmaceutical operations contribute approximately 20-25% of industrial VOC emissions in the city (MPPCB, 2023).

During the COVID-19 lockdown, industrial emissions fell dramatically due to widespread closures. Analysis of satellite imagery and ground monitoring data by Sharma et al. (2021) revealed that areas downwind of industrial clusters in Ujjain showed PM2.5 reductions of 50-60% during the complete lockdown phase, providing further evidence of the substantial contribution of industrial activities to the city's pollution load. As restrictions eased, industrial operations resumed relatively quickly compared to other sectors. By August-September 2020, industrial activities had reached approximately 70-75% of pre-pandemic levels, and by early 2021, most industrial units had resumed full operations. This pattern aligns with the observed rapid rebound in pollutant concentrations, particularly SO2 and industrial-related particulate matter.

4.2 Vehicular Emissions

Transportation emerges as the most significant contributor to certain air pollutants in Ujjain based on the dramatic improvements observed during mobility restrictions. According to Regional Transport Office (RTO) data, Ujjain's vehicular fleet grew by approximately 8-10% annually between 2015-2019, reaching approximately 400,000 registered vehicles by early 2020. Two-wheelers constitute the largest segment (approximately 75%), followed by passenger cars (15%), commercial vehicles (7%), and auto-rickshaws (3%) (RTO Ujjain, 2022). The vehicular contribution to Ujjain's air pollution is particularly evident in the dramatic reductions in NO2 concentrations (65-70%) observed during the strictest lockdown phase when vehicle movement was minimal. Based on source apportionment analysis during and after lockdown periods, vehicular emissions are estimated to contribute:

- 35-40% of NOx emissions
- 40-45% of CO emissions
- 20-25% of PM2.5 emissions
- 15-20% of PM10 emissions
- Significant proportions of VOCs and polycyclic aromatic hydrocarbons (PAHs)

The high proportion of two-stroke and older vehicles in Ujjain's fleet contributes disproportionately to pollution loads. A vehicle emission testing study by Gupta et al. (2022) found that approximately 35-40% of tested vehicles in Ujjain exceeded permissible emission standards, particularly for CO and hydrocarbons. The study also noted that two-wheelers, despite their smaller engine size, contributed approximately 55-60% of total vehicular PM2.5 emissions due to their large numbers and often poor maintenance. Traffic congestion in Ujjain's narrow historical streets further exacerbates vehicle-related emissions. GPS-based traffic flow studies indicate that average vehicle speeds in central areas often fall below 15 km/h during peak hours, significantly increasing emission factors for most pollutants (Transport Department, 2021). The recovery pattern in vehicular emissions following lockdown provides additional insights. Analysis of traffic monitoring data and corresponding pollution levels by Sharma et al. (2022) revealed that by December 2020, traffic volumes had recovered to approximately 75-80% of pre-pandemic levels, while by mid-2021, they had reached 90-95%. However, interestingly, NO2 concentrations (a key marker for vehicular emissions) stabilized at approximately 85-90% of pre-pandemic levels even after traffic volumes fully recovered, suggesting possible lasting changes in transportation patterns or vehicle fleet composition.

4.3 Construction and Road Dust

Construction activities and road dust represent significant contributors to particulate matter pollution in Ujjain. The city experienced substantial infrastructure development in the pre-pandemic period, with municipal records indicating over 200 major construction projects active in early 2020, including commercial developments, residential complexes, and infrastructure upgrades related to the Simhastha Kumbh Mela preparations (Ujjain Municipal Corporation, 2020).

Source apportionment studies suggest that construction activities and road dust collectively contribute:

- 25-30% of PM10 emissions
- 15-20% of PM2.5 emissions

During the COVID-19 lockdown, all construction activities were suspended, resulting in significant reductions in coarse particulate matter. Analysis of PM10/PM2.5 ratios during this period provides insights into the contribution of these sources—the ratio increased from a pre-lockdown average of 1.8-2.0 to 2.2-2.4 during lockdown, suggesting a greater reduction in coarse particles typically associated with construction and road dust (Sharma et al., 2021). As restrictions eased, construction activities resumed gradually. Municipal records indicate that by October-November 2020, approximately 60-65% of pre-pandemic construction projects had resumed, and by mid-2021, construction activities had fully recovered to pre-pandemic levels (Ujjain Municipal Corporation, 2021). This recovery pattern corresponds closely with observed increases in PM10 concentrations during the same period. Road dust emissions are exacerbated by poor road conditions in parts of Ujjain. A survey by the Urban Development Department (2022) found that approximately 30-35% of roads in Ujjain lacked proper paving or maintenance, contributing significantly to resuspended dust during vehicle movement. The correlation between traffic volume recovery post-lockdown and PM10 increases further supports the significance of road dust as a pollution source.

4.4 Domestic and Commercial Fuel Use

Domestic and commercial fuel consumption represents a significant but often overlooked source of air pollution in Ujjain. Despite urbanization, census data indicates that approximately 25-30% of households in Ujjain still rely partially or completely on solid fuels (primarily wood, agricultural residues, and dung cakes) for cooking and heating purposes (Census of India, 2011).

Based on emission inventory studies, domestic fuel combustion is estimated to contribute:

- 10-15% of PM2.5 emissions
- 8-10% of PM10 emissions
- 15-20% of CO emissions
- 5-8% of NOx emissions

During lockdown periods, domestic emissions likely increased in residential areas as people spent more time at home, potentially offsetting some reductions from other sectors. This pattern has been observed in studies across Indian cities, where satellite observations revealed increased signals of biomass burning in residential areas during lockdown periods (Beig et al., 2021). Commercial establishments, particularly restaurants, bakeries, and small-scale food processing units, contribute significantly to local pollution hotspots. These sources typically use a mix of LPG, wood, and other biomass fuels. During lockdown, these emissions decreased substantially as establishments closed, but they recovered rapidly during the unlock phases as food businesses were among the first to resume operations. The seasonal variation in domestic fuel use is particularly noteworthy in Ujjain. During winter months (November-February), biomass combustion for heating increases substantially, contributing to the seasonal spike in particulate matter concentrations. This pattern was observed even during partial lockdown periods in winter 2020-2021, contributing to the seasonal deterioration in air quality despite ongoing restrictions in other sectors.

4.5 Agricultural Activities and Biomass Burning

Agricultural activities in the peri-urban and surrounding rural areas of Ujjain contribute significantly to seasonal air pollution episodes. Ujjain district encompasses approximately 6,091 km² of land, with approximately 60% devoted to agricultural use (Agricultural Department, Madhya Pradesh, 2020). The dominant crops include soybean, wheat, and various pulses. Seasonal agricultural residue burning, particularly after wheat and soybean harvests, creates episodic pollution events. Satellite fire counts and corresponding air quality data analysis by Sharma et al. (2022) identified clear correlations between agricultural burning periods and PM2.5 spikes in Ujjain, particularly during:

- October-November (post-soybean harvest)
- April-May (post-wheat harvest)

During these periods, agricultural burning is estimated to contribute:

- 20-25% of PM2.5 during burning episodes
- 15-20% of PM10 during burning episodes
- Significant black carbon and organic carbon emissions

The lockdown period coincided with the wheat harvest season in 2020, but restrictions on movement likely reduced monitoring and enforcement capabilities regarding agricultural burning. Satellite observations indicated that agricultural burning incidents decreased only marginally (10-15%) during this period compared to previous years, suggesting that this source remained relatively constant while other anthropogenic sources decreased dramatically (MPPCB, 2021). As a semi-arid region, Ujjain also experiences significant dust emissions from agricultural fields, particularly during land preparation activities and in fallow periods. These emissions are highly dependent on meteorological conditions, with wind erosion during dry periods contributing substantially to background PM10 levels.

5. IMPACT ON AIR QUALITY PARAMETERS

5.1 Particulate Matter (PM10 and PM2.5)

Particulate matter represents the most concerning air pollutant in Ujjain due to its consistent exceedance of national standards and documented health impacts. Analysis of PM dynamics during the COVID-19 natural experiment provides valuable insights into anthropogenic contributions.

5.1.1 PM10 Dynamics

Pre-COVID monitoring data (2018-2019) showed that Ujjain's annual average PM10 concentration typically ranged from 110-130 μg/m³, significantly exceeding the NAAQS annual standard of 60 μg/m³. During the initial complete lockdown phase, PM10 concentrations decreased dramatically to 45-55 μg/m³, representing a 52-58% reduction. Time-series analysis revealed that PM10 reductions were most pronounced during normally high-traffic periods (morning and evening rush hours), decreasing by 60-65% during these intervals, while reductions during midday periods were less dramatic (40-45%). This pattern suggests the significant contribution of traffic and associated road dust to PM10 levels (Sharma et al., 2021).

As restrictions eased, PM10 concentrations increased incrementally:

- Phase 2-3 (April 15 - May 17, 2020): Average PM10 concentrations increased to 55-65 μg/m³
- Phase 4 and early Unlock phases (May-July 2020): Average PM10 concentrations reached 65-80 μg/m³
- By Diwali 2020 (November): PM10 concentrations reached 90-110 μg/m³, approximately 70-80% of pre-pandemic levels for that season

The recovery pattern for PM10 closely tracked the resumption of construction activities and traffic volumes, highlighting these sectors as primary contributors. By late 2021, PM10 concentrations had largely returned to pre-pandemic seasonal patterns, though winter peak concentrations remained approximately 5-10% below pre-2020 levels through 2022-2023.

5.1.2 PM2.5 Dynamics

Fine particulate matter (PM2.5) showed similar but slightly different patterns compared to PM10. Pre-pandemic annual average PM2.5 concentrations in Ujjain typically ranged from 55-70 µg/m³, well above the NAAQS annual standard of 40 µg/m³. During the strictest lockdown phase, PM2.5 concentrations decreased to 20-30 µg/m³, representing a 48-55% reduction. Spectroscopic analysis of collected PM2.5 samples before and during lockdown revealed significant reductions in black carbon content (60-65% reduction) and trace metals associated with vehicular emissions, including lead, copper, and zinc (50-55% reduction). Conversely, the proportion of secondary organic aerosols and soil-derived components in PM2.5 samples increased during lockdown periods, suggesting these sources remained relatively constant while anthropogenic primary emissions decreased (Patel et al., 2021).

The recovery of PM2.5 levels followed a slightly different trajectory compared to PM10:

- By late 2020, PM2.5 had recovered to approximately 65-70% of pre-pandemic levels
- By mid-2021, PM2.5 had reached 80-85% of pre-pandemic concentrations
- By winter 2021-2022, PM2.5 concentrations reached approximately 90-95% of pre-pandemic winters

This slower recovery compared to PM10 suggests that some sources of fine particulate pollution (particularly industrial and vehicular emissions) may have experienced more lasting changes following the pandemic.

6. CONCLUSION

The COVID-19 lockdowns provided a natural experiment to analyze air quality dynamics in Ujjain, highlighting the significant role of human activities in pollution accumulation. The study found that air quality improved dramatically during the strict lockdown phases due to reduced vehicular traffic, industrial operations, and construction activities. NO2 and CO levels showed the most substantial declines, reflecting the dominant role of vehicular emissions in urban air pollution. However, as restrictions eased, pollution levels gradually rebounded, with industrial and vehicular emissions recovering more rapidly than other sources. Despite the return to pre-pandemic activity levels, long-term trends indicate that average pollution levels remain marginally lower than pre-2020 benchmarks. Factors such as increased work-from-home policies, greater adoption of digital services, and growing environmental awareness have contributed to this shift. Comparative analysis with other cities suggests that Ujjain, with its mixed economic base, experienced sharper pollution declines during lockdown but a faster rebound post-pandemic compared to industrial-heavy cities like Kota.

The identification of key pollution sources—including vehicular emissions, industrial activities, biomass burning, and construction dust—emphasizes the need for targeted mitigation strategies. Strengthening vehicular emission regulations, promoting cleaner industrial technologies, enforcing construction dust control measures, and regulating biomass burning can help sustain the air quality improvements observed during the lockdown period. Moving forward, policymakers and urban planners must capitalize on these insights to develop sustainable air quality management strategies. Implementing long-term air pollution control measures will be crucial for maintaining health and environmental benefits beyond the pandemic period. By integrating technological advancements, behavioral shifts, and regulatory enforcement, Ujjain can work towards achieving consistently lower pollution levels and improved public health outcomes.

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