PAHAL HORIZON
An International Research Journal
Homepage: www.pahalhorizon.com

Agra's Air Pollution Challenge At Toll Stations: Green Manufacturing, Policy, And Ecosystem Restoration Strategies

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ABSTRACT

Rapid industrialization and motorization in Agra, Uttar Pradesh, India, have intensified particulate matter (PM) pollution, particularly fine particulate matter (PM2.5), threatening air quality, climate, public health, and the iconic Taj Mahal. PM2.5, with its high surface-to-mass ratio and deep lung penetration, binds toxic heavy metals (e.g., Pb, Cr, Cd, Cu, Zn, Fe), which persist, bioaccumulate, and contribute to cardiovascular diseases, chronic respiratory conditions, and lung cancer. In Agra, dominant sources include vehicle emissions from heavy traffic on highways like NH-44, congestion near The Taj Mahal, and the Yamuna Expressway, alongside industrial activities such as leather tanneries, foundries, marble polishing, and shoe manufacturing. These generate pollution through exhaust, dust resuspension, combustion, and emissions. Studies report elevated PM2.5 levels (often 100 to 200+ $\mu g/m^3$ seasonally, with peaks exceeding 400 $\mu g/m^3$ in winter at traffic sites), enriched heavy metals from anthropogenic sources (traffic, industries), and high health risks including elevated hazard quotients and lifetime cancer risks, especially from finer particles. Occupational exposure in traffic-heavy zones and industries heightens oxidative stress and health risks for workers, residents, and tourists. Adopting green manufacturing and building a sustainable ecosystem are essential for mitigation. Green manufacturing promotes cleaner production, resource efficiency, waste minimization, emission controls, and circular economy practices. Uttar Pradesh initiatives include integrated manufacturing clusters in Agra, land allocation for non-polluting green units, renewable energy promotion (e.g., solar projects), and policies for sustainable leather/footwear sectors (e.g., effluent treatment, low-chemical processes, eco-friendly technologies). These align with national efforts like Make in India, PM Gati Shakti, and the Taj Trapezium Zone (TTZ) regulations restricting polluting industries, mandating scrubbers/filters, vehicle restrictions, and heritage protection. Implementing these reduces PM2.5 and heavy metal emissions, improves air quality, safeguards vulnerable populations, supports tourism, and fosters resilient communities. Integrating technological innovation, policy enforcement, ecosystem restoration (e.g., Yamuna rejuvenation, green corridors), and sustainable practices enables Agra to balance economic growth with cleaner air and long-term environmental health.

*Keyword***:** Air Pollution, Green manufacturing, Heavy metals, Sustainable Ecosystem.

1. INTRODUCTION

Agra, a UNESCO World Heritage city, annually attracts millions of tourists, yet it grapples with severe and chronic air pollution. Ambient particulate matter concentrations consistently exceed international guidelines; for instance, annual PM2.5 averages frequently range between 80 to 100+ µg/m³, which is 2 to 10 times higher than the World Health Organization guideline of 5 to10 µg/m³. Similarly, PM10 levels often reach 150 to 300+ µg/m³. These elevated pollution levels are exacerbated by seasonal factors, including winter inversions and post-monsoon agricultural stubble burning, alongside emissions from local sources. A significant contributing factor to localized air pollution are toll plazas situated on major highways, such as the Yamuna Expressway and NH-2. These locations act as emission hotspots where idling and accelerating vehicles contribute substantially to exhaust and non-exhaust emissions, including road dust resuspension (Munjal et al., 2022; Nazneen et al., 2023). The deposition of light absorbing dust and carbonaceous particles, such as black carbon and brown carbon from fossil fuel and biomass combustion, is responsible for the surface discoloration of the Taj Mahal (Bergin et al., 2014). Some research indicates elevated PM2.5 many times from prescribed limits during haze periods versus non-haze periods), with metals such as Cr, Cd, Ni, Pb, Fe, Zn, Mn, and Cu showing strong correlations with oxidative potential and increased health risks. Enrichment factors for Cd, Cr, Pb, Zn, and Cu, particularly in finer fractions, suggest a predominant anthropogenic origin. The challenge of balancing economic growth with environmental protection is not unique to Agra. Globally, rapid industrial development has led to widespread ecological degradation. The process of industrialization and urbanization accelerates the concentration of population in cities, resulting in large quantities of industrial and urban waste. The environment's inability to absorb these wastes becomes a significant pollutant damaging urban landscapes and polluting the environment (Wang, 2020). This has contributed to ecological and environmental issues that have worsened as more nations and areas have industrialized (Rizwanullah et al., 2024). For cities facing intensive industrial activities, sustainable development has emerged as a global problem, often leading to a dilemma of economic slowdown coinciding with environmental degradation.

This situation underscores a common problem for polluted cities worldwide: the deterioration of natural amenities due to rapid industrial development and urbanization (Mondal & Das, 2018). In Agra, facing significant economic and environmental pressures, the government has implemented various air pollution control policies. These measures include major structural adjustments in industrial sectors, such as phasing out inefficient coal-fired power plants and small-scale coal mining, aimed at controlling the production capacity of high-polluting industries and updating end-of-pipe treatment technologies (Shu et al., 2022). While these initiatives have played an important role in controlling air pollution, their implementation has sometimes increased the burden of economic output of the industry and unemployment in the region due to production capacity limitations, indicating that these measures have not always adequately solved the problems arising from unbalanced economic and environmental development in polluted cities. Achieving the dual goals of economic growth and environmental improvement necessitates policies that aim at maximizing economic benefits while minimizing associated adverse environmental impacts. Such approaches require continuous evaluation to determine optimal development paths for polluted cities in the long term (Irsyad et al., 2019). This review aims to further analyze the environmental and economic benefits of technological progress by employing dynamic simulation to explore an optimal economic transformation path. This research seeks to address the dilemma of economic decline and environmental degradation prevalent in heavy industry-dominated cities through the establishment of a green economy transformation decision-making model.

Air Pollution Profile: Levels, Trends, and Sources

Particulate matter is the predominant air pollutant cities like Agra. Annual average concentrations of urban PM typically range from 150 to 200 µg/m³ annually; PM2.5 from 90 to105 µg/m³ (Kulshrestha et al., 2009). These figures often exceed prescribed standards set by organizations like the World Health Organization and India's Central Pollution Control Board (Kulshrestha et al., 2009; Pipal et al., 2014; Sah, 2022). Post-monsoon and winter seasons often exhibit significantly higher concentrations. For PM, winter concentrations have been observed as high as 328.9 to 384.5 µg/m³ and post-monsoon concentrations at 252.25 to 337.88 µg/m³, falling within the 250 to 400 µg/m³ range (Pipal et al., 2014). These elevated levels are primarily attributed to atmospheric inversion, extensive biomass burning, and regional pollutant transport (Pipal et al., 2014). Source apportionment studies, including those relevant to Agra and the surrounding region, indicate the following general contributions to PM pollution (Nagar et al., 2020; Pant & Harrison, 2011; Pipal et al., 2014; Sharma et al., 2023):

Road dust/soil resuspension: often a significant contributor, with some studies showing crustal material contributing up to 55% to PM (Nagar et al., 2020).

Vehicular emissions: contributing substantially, with some estimates reaching around 60% of pollution in Agra due to vehicles (Pipal et al., 2014). Industries/coal combustion: contributing to overall pollution (Pant & Harrison, 2011). Biomass/crop residue burning: a known contributor in the Indo-Gangetic Plain (Pachauri et al., 2013; Pant & Harrison, 2011).

Heavy metals detected in PM, such as lead, zinc, iron, manganese, chromium, copper, nickel, and cadmium, show a dual origin. Crustal elements like aluminum, Fe, and calcium are naturally occurring, while elevated levels of Pb, Cd, and Cr often signify anthropogenic enrichment from vehicular emissions and industrial processes (Liu et al., 2025; Matei et al., 2025; Shikha et al., 2023). Fine particulate matter (PM) is particularly concerning due to its higher toxic metal fractions (Shikha et al., 2023).

Health and Environmental Impacts

PM-bound metals pose significant health risks as they can penetrate deep into the lungs, enter the bloodstream, and induce oxidative stress, inflammation, and bioaccumulation (Li et al., 2013; Liu et al., 2025). Key health concerns include:

Public Health: Increased incidence of cardiovascular diseases, chronic respiratory issues, lung cancer, and neurological effects (Li et al., 2013). Hazard indices for certain metals have been found to exceed 1 in PM, indicating potential non-carcinogenic health impacts (Shikha et al., 2023a, 2023b). Carcinogenic risks from certain metals, particularly Cr, are also a concern for both adults and children (Shikha et al., 2023a, 2023b). Vulnerable populations include traffic workers, residents near highways, industrial laborers, and tourists.

Ecosystem Disruption: Metal deposition impacts soil quality, contaminates Yamuna River sediments, and affects vegetation. These metals can inhibit microbial activity, reduce primary productivity, disrupt nutrient cycling, and impair trophic energy transfer (Li et al., 2013; Matei et al., 2025). Legacy contamination in agro-ecosystems leads to metal entry into food chains, exacerbating long-term risks.

Cultural Heritage: Elevated PM and metal concentrations contribute to the discoloration (yellowing from soot and acid deposition) of the Taj Mahal, threatening its longevity despite protective measures within the Taj Trapezium Zone (M. I. A. M. Arif et al., 2023; Mohd. Arif et al., 2024; "Black Carbon, Dust Discolouring Taj Mahal," 2014; Vij, 2023).

Occupational exposure in high-traffic and industrial zones significantly heightens health risks, with finer particles posing greater threats due to their larger surface area and increased bioavailability.

Particulate Matter-Bound Heavy Metals at Toll Plazas

Toll plazas represent significant hotspots for amplified pollutant exposure. Vehicles frequently queue, and idling engines emit PM enriched with metals originating from fuel combustion, lubricants, and wear (Tanvir et al., 2020). Studies conducted at general Indian toll plazas report that PM2.5 concentrations inside booths can be higher than at the kerbside (Nazneen et al., 2023). Specifically, some studies indicate that PM concentrations for booth workers can be 1.1 to 1.35 times higher than outside levels, and black carbon concentrations up to 2 to 3 times higher (Nazneen et al., 2023). Pulmonary deposition models suggest a 50 to 75% higher pollutant dose for booth workers compared to those outside (Tanvir et al., 2020). In the context of Agra, with its high volume of diesel and commercial traffic on expressways, similar hotspots at intersections and toll points exhibit PM and PM1.0 to 0.5 fractions with metals yielding Hazard Quotients greater than 1 (Shikha et al., 2023; Tiwari et al., 2021) and Excess Lifetime Cancer Risk exceeding many times (Tiwari et al., 2021).

Primary sources of these metals include: Vehicular exhaust: Pb and Zn from fuel combustion and older catalysts (Lin et al., 2015; Nicolas et al., 2020; Rogula-Kozłowska et al., 2015).Brake wear: Cu and antimony (Amato et al., 2008; Nicolas et al., 2020). Tire wear: Zn (Amato et al., 2008; Rogula-Kozłowska et al., 2015).Resuspension: Fe, Mn, and other crustal elements (Nicolas et al., 2020; Rogula-Kozłowska et al., 2015).

Winter months exacerbate metal enrichment due to reduced atmospheric dispersion. Smaller particles (<1 µm) are particularly concerning as they penetrate deeper into the respiratory system, increasing systemic toxicity. Health risks for toll workers include elevated reactive oxygen species, oxidative stress, and an increased likelihood of respiratory and cardiovascular issues. Nearby communities also face chronic exposure. While a specific Agra-based toll plaza study is lacking, data from traffic intersections in Northern India and general toll assessments confirm the high risk associated with such sites.

Fig: Pollution at toll plazas
Source: pixelcase.com

Impacts on Heritage, Health, and Ecosystem

Heritage: The architectural integrity and aesthetic appeal of the Taj Mahal are significantly threatened by atmospheric pollution. Discoloration of its white marble surfaces stems primarily from the deposition of light-absorbing particulate matter, including black carbon, light-absorbing organic carbon (brown carbon, BrC), and dust, largely originating from the combustion of fossil fuels and biomass (Bergin et al., 2014). This deposition diminishes the marble's natural reflectance and alters its perceived color (Bergin et al., 2014). Additionally, acidic gases, specifically sulfur dioxide and nitrogen oxides, emitted from local sources, exacerbate the chemical etching and degradation of the marble, impacting cultural heritage and urban aesthetics (Nagar et al., 2020).

Health: Exposure to fine particulate matter (PM2.5), particularly those associated with bound metals, poses a critical public health challenge in India. These pollutants are definitively linked to a range of severe health outcomes, including respiratory diseases, cardiovascular issues, and an increased risk of cancer. Epidemiological studies indicate that PM2.5 exposure contributes to approximately 1.67 million premature deaths annually in India (Shukla et al., 2025), with millions more imperiled by concentrations exceeding national ambient air quality standards (Bangar et al., 2021). The toxicity of PM2.5 is not solely dependent on its mass concentration but significantly on its elemental composition, especially the presence of trace metals like lead, cadmium, and mercury, which are concerning due to their potential for bioaccumulation in human organs (Bangar et al., 2021; Shukla et al., 2025). Moreover, certain occupational groups, such as toll workers in areas like Agra, face substantially higher risks, with exposure levels reported to be 2 to 3 times greater than the general population.

Ecosystem: The Yamuna River's severe pollution, primarily from untreated sewage and industrial effluents, exacerbates regional environmental issues. Reduced river flow, often a consequence of diversion and climate change, directly impacts water quality by increasing the concentration of pollutants, nutrients, and salinity (Patil et al., 2021; Puczko & Jekatierynczuk-Rudczyk, 2020; Rolls et al., 2012). This low flow also adversely affects air quality by altering local microclimates, which can hinder the dispersion of pollutants and contribute to the formation and persistence of urban smog (Rico et al., 2025; Ulpiani et al., 2021). The cumulative stress from acid deposition and metal contamination leads to significant biodiversity loss, disrupting aquatic and riparian ecosystems.

Green Manufacturing as a Mitigation Strategy

Green manufacturing presents a robust framework for addressing environmental degradation by promoting cleaner production, resource efficiency, emission controls, and circular economy principles (Bapat et al., 2024; Shukla et al., 2023). This approach aims to curb PM-bound metal emissions at their source, simultaneously minimizing waste and pollution while offering financial gains and enhancing the image of industries (Seth et al., 2018; Shukla et al., 2023).

Uttar Pradesh Initiatives

The Uttar Pradesh Footwear, Leather, and Non-Leather Sector Development Policy 2025 actively encourages the adoption of eco-friendly technologies, advanced effluent treatment systems, and low-chemical processes. The policy provides substantial incentives, including capital and land subsidies up to 80% for cluster-based developments, particularly in key industrial hubs such as Agra (a major footwear manufacturing center), Kanpur, and Unnao. While aiming to create over 2.2 million jobs, this policy also enforces stringent environmental standards like zero-liquid discharge and reduced hazardous input usage.

Integrated Manufacturing Clusters

The Integrated Manufacturing Clusters planned are designed to house non-polluting industrial units. These clusters strictly adhere to Taj Trapezium Zone regulations, mandating the use of advanced pollution control technologies such as scrubbers and filters, a transition to natural gas, and limits on vehicular emissions. Furthermore, IMCs promote the integration of renewable energy sources, especially solar power, and embrace circular economy practices, including waste minimization and recycling, to significantly reduce their environmental footprint.

Sector-Specific Advances

The leather and footwear sectors are implementing significant advancements in sustainable practices. These include the adoption of salt-free tanning and enzyme-based unhairing processes, which drastically reduce chemical consumption. For wastewater treatment, physio-remediation techniques and electro-oxidation methods are being employed to achieve zero-liquid discharge (Bhardwaj et al., 2023; Rajamani, 2016). The industry also faces the challenge of managing substantial waste; for instance, Agra alone generates approximately 45 tonnes of footwear waste daily. While informal recycling exists, there is a clear need for formal systems to process materials like leather (40%) and synthetics (Kanagaraj et al., 2014; SI et al., 2018). Furthermore, research is exploring novel eco-friendly approaches for treating leather industry wastewater using plant extracts and nanoparticles (Al-Hussain et al., 2025). These sector-specific efforts align with national initiatives such as "Make in India" and "PM Gati Shakti," as well as TTZ regulations, with the potential to significantly reduce PM and metal emissions while fostering economic growth.

Ecosystem Energy Restoration Approaches

Restoring ecosystem energy flows, encompassing primary production, trophic efficiency, and nutrient cycling, necessitates comprehensive and integrated efforts.

Yamuna Rejuvenation

Ongoing projects aimed at rejuvenating the Yamuna River focus on sewage treatment, interception of drains, revival of natural wetlands, and floodplain afforestation. These initiatives are critical for reducing metal deposition, enhancing the river's self-purification capacity, and restoring vital aquatic and riparian habitats (Sharma et al., 2024).

Green Corridors and Nature-Based Solutions

The establishment of riparian buffers, urban forests, and biodiversity parks along the Yamuna creates essential eco-corridors. These green infrastructures not only enhance carbon sequestration but also effectively intercept airborne pollutants and improve air quality. Native vegetation plays a crucial role through phytoremediation, stabilizing and extracting heavy metals from contaminated soils, thereby contributing to ecological recovery.

Holistic Integration

A holistic approach involves integrating upstream green manufacturing practices to prevent new pollutant inputs, thereby accelerating natural attenuation processes within the ecosystem. When combined with robust policy enforcement (e.g., TTZ, Namami Gange), active community participation, and continuous environmental monitoring, these strategies collectively rebuild ecosystem resilience.

2. CHALLENGES AND RECOMMENDATIONS

Significant challenges persist in implementing these mitigation strategies, including the pervasive issue of legacy pollution, ensuring compliance within the informal sector, managing winter biomass burning, and addressing existing enforcement gaps in environmental regulations (Gujral et al., 2025).

Future efforts must prioritize: Strengthening real-time monitoring and conducting thorough source apportionment studies to accurately identify pollution origins. Scaling up the adoption of green technologies through targeted subsidies and comprehensive training programs. Prioritizing the ecological restoration of the Yamuna River through the implementation of green infrastructure projects. Strictly enforcing TTZ regulations while carefully balancing socio-economic considerations and livelihoods.

Agra's sustainable future hinges on a synergistic approach that combines green manufacturing (focused on emission prevention) with ecosystem restoration (aimed at environmental recovery). This integrated strategy holds the promise of safeguarding public health, preserving the Taj Mahal, revitalizing the Yamuna, and fostering sustainable growth in one of India's most historic cities.

3. STRATEGIES FOR MITIGATION

Green Manufacturing: Industries surrounding Agra, including glass, foundries, leather, and brick kilns, significantly contribute to pollution through their reliance on coal and coke. Green manufacturing advocates for cleaner production methods such as energy-efficient technologies, waste minimization, and the adoption of low-emission fuels. The mandated shift to natural gas and compressed natural gas within the TTZ has demonstrably reduced sulfur dioxide and particulate matter emissions from some industrial units. Furthermore, implementing advanced flue gas recirculation, bag filters, and electrostatic precipitators is crucial for effective PM control. Circular practices, such as recycling process waste and utilizing biomass briquettes, are also encouraged. Incentives like subsidies for solar integration and ISO 14001 certification further promote the adoption of sustainable practices. Broader adoption of these strategies could lead to a significant reduction of industrial PM by an estimated 30–50% (as per NEERI estimates).

4. POLICY INTERVENTIONS

Taj Trapezium Zone: Established as a 10,400 km^2 protected area following a 1996 Supreme Court ruling, the TTZ strictly prohibits the use of coal and coke, mandates natural gas as fuel, restricts the establishment of new polluting industries, enforces the use of CNG vehicles, and limits tree felling.

National Clean Air Programme: Agra's city action plan under the NCAP aims for a 20–30% reduction in PM concentrations by 2024–2026.

Key measures include:

Vehicular Pollution: Implementation of BS-VI norms, promotion of CNG buses and electric vehicles, and trials of odd-even schemes. Dust Management: Mechanized sweeping, water sprinkling on roads, and road paving. Construction Activities: Covering stockpiles of materials and using mist guns to suppress dust. Biomass Burning: Promoting LPG usage and implementing stubble management practices.Industrial Emissions: Enforcing stricter emission standards and mandating online monitoring.

Despite these policies, implementation gaps persist, as highlighted by criticisms from the National Green Tribunal. However, the TTZ has successfully curtailed some industrial emissions. Recent efforts also focus on improving traffic management at toll plazas, for instance, through the use of FASTag to reduce vehicle idling.

Ecosystem Restoration

Afforestation initiatives create crucial green belts, where roadside plantations effectively filter particulate matter through deposition on leaves. The Yamuna Action Plans are designed to reduce sewage inflow, restore natural river flow, and enhance aeration, thereby improving the river's microclimate. Urban forestry promotes the planting of native species such as neem and peepal, particularly near highways and toll plazas, to maximize pollutant absorption. Wetland and riverbank restoration efforts leverage phytoremediation to absorb heavy metals from contaminated areas. Community involvement, through initiatives like Miyawaki-style dense forests and citizen monitoring programs, further strengthens these restoration efforts. Integrated approaches, such as incorporating green infrastructure at toll plazas, could locally reduce PM concentrations by 20 to 40%.

5. CONCLUSION

Agra's severe air pollution, particularly its amplification by PM-bound heavy metals at toll plazas, poses a critical threat to public health, invaluable heritage, and the regional economy. Combating this multifaceted challenge requires a synergistic approach, integrating green manufacturing, robust policy frameworks, and extensive ecosystem restoration. Achieving success in these efforts necessitates rigorous enforcement, widespread technology adoption, active public participation, and comprehensive airshed-level coordination. Only through sustained, collaborative action can Agra's air quality be restored and its invaluable legacy safeguarded. Ultimately, cities grappling with significant air pollution often experience hindered economic development and mounting pressure from both local communities and external stakeholders to prioritize environmental protection.

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