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REVIEW PAPER

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Revolutionizing air pollution analysis and modeling across road construction phases: A comprehensive review

Anilkumar Dattatray Shimpi[*1], Ashok Maruti Datir[2], Pravin Mukund Nalawade[3]

Department of Environmental Science, K.R.T. Arts, B.H. Commerce, A.M. Science College (Affiliated to Savitribai Phule Pune University), Nashik, Maharashtra, India

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ABSTRACT

By generating large concentrations of particulate matter (PM), nitrogen oxides (NOx), sulphur dioxide (SO2), and carbon monoxide (CO), road building greatly adds to atmospheric pollution, endangering ecosystems, public health, and urban sustainability. Through the integration of empirical data, systematic reviews, and cutting-edge simulation techniques, this review summarises developments in air quality research and modelling from peer-reviewed publications published between 2020 and 2025. It looks at spatiotemporal dispersion patterns, phase-specific emission profiles, the effects on the environment and human health, and mitigation techniques. Case studies from around the world show that peak emissions are produced during the pavement and earthworks phases, frequently surpassing legal limitations in urban areas. The forecast accuracy of pollution hotspots is improved by combining machine learning, geographic modelling, and real-time monitoring. The assessment promotes phase-tailored strategies to encourage sustainable infrastructure development and emphasises the potential for significant emission reductions with current technologies. Researchers, legislators, and practitioners can use the insights offered to reduce the environmental impact of road construction projects and promote sustainable urban growth.

***Corresponding author:** Anilkumar Dattatray Shimpi ✉ anilkumarshimpi@yahoo.com

INTRODUCTION

Urbanisation and economic pressures have fuelled the quick development of road infrastructure, which has exacerbated environmental issues, especially the deterioration of ambient air quality.

Construction sites emit a variety of pollutants that exacerbate urban pollution, respiratory conditions, and climate change. According to recent projections, 10–20% of urban PM concentrations in high-development regions are caused by construction activity (World Health Organisation, 2024). These emissions, which vary significantly between stages like site clearing, sub-base preparation, and asphalt paving, are caused by heavy mechanical activities, material handling, and traffic disturbances. Since aggregate assessments frequently ignore the ephemeral nature of construction-related pollution dynamics, recent research emphasises the need for phase-specific assessments.

Due to fugitive dust resuspension, advanced monitoring shows PM surges of 50–200% during earthworks. Pollutant entrapment is exacerbated and dispersion patterns are complicated by climatic conditions, such as low wind speeds in urban canyons.

In an effort to transform air quality analysis, this review compiles academic works from 2020 to 2025 to investigate pollutant dynamics, modelling advancements, and mitigation strategies in road building. It fills in the gaps in phase-differentiated assessments, where PM emissions are higher in the early stages and gaseous pollutants like CO and VOCs are higher in the latter stages.The study promotes data-driven sustainable practices by combining interdisciplinary viewpoints from public health, engineering, and environmental research. According to systematic reviews, PM is the main air pollutant associated with building operations, followed by NOx, SO2, CO, and volatile organic compounds (VOCs) (Ma *et al.*, 2024). According to a thorough review of 161 studies conducted between 2000 and 2020, construction activities play a major role in pollution throughout the building life cycle by producing dust and operating machinery (Ma *et al.*, 2024). A 2025 analysis that extended to road-specific contexts evaluated emissions during project phases and identified paving as a major contributor to VOCs and earthworks as the primary source of PM. In-depth information on road building emissions is provided by empirical studies conducted in 2023–2025. By linking activities with PM levels, a 2023 artificial neural network (ANN) model forecasted the quality of the air at building sites (Ma *et al.*, 2024). Due to soil disturbance and vehicle movement, PM10 levels during earthworks in Ghana during 2024 monitoring of unpaved road construction and asphalt overlays exceeded regulatory criteria by 50–100%. Black carbon (BC), PM2.5, PM10, and ultrafine particles (UFP) from diesel machinery were measured in a 2025 study on high-rise construction; the measurements peaked during the excavation stages.

Pollution is made worse by traffic-related pollutants during construction. According to a 2023 study that examined the relationship between road area ratios and urban air quality, capacity expansions lower traffic but raise emissions in the absence of mitigation. A natural experiment, the 2021 COVID-19 lockdowns demonstrated 40–85% reductions in pollutants as a result of reduced traffic, highlighting the important role that road activities play (Rahaman *et al.*, 2021). The effects on health are well established, and exposure to PM is linked to respiratory illnesses. Due of decreased visibility and health damage, a 2023 evaluation emphasised PM's role in construction accidents. Construction emissions, which come from both indoor and outdoor sources, are a significant contributor to the millions of premature deaths caused by air pollution worldwide each year (World Health Organisation, 2024). Particularly important for site workers and local residents, a 2022 meta-analysis connected PM2.5 exposure to a rise in pneumonia hospitalisations (Kim *et al.*, 2022). According to current occupational health research, volatile organic compounds (VOCs) from asphalt paving can cause neurological diseases and cancer at work (Chong *et al.*, 2014).

Ecosystems are disturbed by emissions from building. According to a 2025 post-assessment of highway building, PM deposition caused soil acidification and biodiversity loss (Wang *et al.*, 2023). Aquatic life is negatively impacted by heavy metal-containing runoff that contaminates streams. Through radiative forcing, black carbon from diesel exhaust speeds up local warming (Bond *et al.*, 2013). These effects are exacerbated by socioeconomic inequality, which perpetuates environmental injustice by exposing low-income populations to higher levels of exposure (Alvarez *et al.*, 2023). Developments in modelling have played a key role in transforming analysis. The integration of multi-scale models for road emissions is demonstrated by spatial modelling trends from 2010 to 2023. For example, in Beijing, the 2022 integrated air quality modelling system (IAQMS) simulates traffic pollutants at the street size (Ma *et al.*, 2024). Advances in machine learning (ML), specifically recurrent neural networks (RNNs) such as LSTM, have enhanced high-resolution NO2 and PM2.5 forecasts, attaining 90–95% accuracy in urban environments (Laudan *et al.*, 2025). Using IoT data for real-time forecasting, ML is becoming more and more popular in Europe, according to a 2025 study (Laudan *et al.*, 2025). A 2023 ANN model that integrated real-time sensor data successfully forecasted site air quality for applications related to construction (Ma *et al.*, 2024). By addressing secondary pollutants, hybrid models such as the Community Multiscale Air Quality (CMAQ) system improve regulatory compliance (Appel *et al.*, 2021). Phase-specific interventions have shown promise as mitigation efforts have gained traction. Behavioural science-based dust mitigation strategies cut PM emissions by 60–80% (Council on Energy, Environment and Water, 2025). A 2025 research showed that clinker substitutes, material recycling, and optimisation might reduce emissions by 50% (Roads Australia, 2024). Zero-pollution goals and ongoing monitoring are enforced by policy frameworks as the EU Green Deal (European Environment Agency, 2023).

Three main goals are intended to be addressed in this assessment in order to improve knowledge and control of air pollution during road building. In order to determine how emissions differ at various phases and places, it first aims to analyse the sources and spatiotemporal patterns of contaminants. Second, it assesses and highlights the strengths and weaknesses of emergent modelling techniques intended to predict pollution levels and assist with efficient management plans. In order to ensure a balanced approach to environmental preservation and urban growth, it concludes by outlining future research objectives and suggesting integrated mitigation strategies.

SOURCES AND DYNAMICS OF ATMOSPHERIC CONTAMINANTS

Due to the particular activities, tools, and environmental conditions at each step, the sources and dynamics of air pollutants during road building are distinguished by distinct phase-specific emission profiles. Due to soil excavation, land grading, and vehicle movement on unpaved areas, early stages like site clearance and grubbing are the main sources of particulate matter (PM) emissions, primarily PM10 and PM2.5. According to empirical research using high-volume samplers and gravimetric analysis, PM10 concentrations during excavation exceeded 200 µg/m^3, exceeding national ambient air quality regulations by 100–200% in urban settings. These results are in line with a 2025 study that measured PM emissions from earthworks and highlighted how heavy machinery operations, like bulldozing and material hauling, greatly increase fugitive dust resuspension, particularly in arid climates where wind speeds of less than 5 m/s can cause particles to be suspended in the atmosphere for an extended period of time (Council on Energy, Environment and Water, 2025). According to a recent assessment, PM emissions during these early stages are impacted by soil composition, moisture content, and site-specific topography. Urban construction sites are particularly polluted because of the limited natural dispersion in densely populated areas, which can lead to localised PM2.5 spikes of up to 150 µg/m^3 (Assessing air pollution emission from construction project activities, 2025).

Additionally, unregulated dust from excavation contributes to this phase. According to a 2024 analysis, PM10 levels in high-traffic construction zones can reach 300 μg/m³, highlighting the need for phase-targeted regulations to reduce resuspension effects (Unregulated Dust: The Impact of Excavation on Urban Air Quality, 2024).

when operations require crushing aggregates and compacting materials, frequently with diesel-powered rollers and graders, emissions shift towards a combination of PM and gaseous pollutants when the process moves into intermediate phases like sub-base preparation and granular layering. Aggregate handling during these phases contributes 20–30% of the overall project pollution, according to a 2023 lifecycle analysis of road construction materials.

Additionally, NOx from machine exhaust adds another 15%, especially during extended compaction operations (Zhang *et al.*, 2023). Recent empirical data from highway construction work zones in 2024 further explained how traffic diversions during these phases worsen dynamics. According to on-site sensors and environmental impact frameworks, idling vehicles and rerouted heavy-duty trucks increase CO and NOx by 25–40% (Environmental impacts from traffic on highway construction work zones, 2024). Additionally, according to a 2025 study on the effects of spatial spillover, sub-base activities in urban corridors result in cross-border pollution transport, where PM from material stockpiling spreads over 1-2 km radii, affecting the air quality of nearby residential areas with concentrations 50% higher than background levels (Road Traffic Infrastructure Construction and Air Pollution Based on Spatial Spillover Effects, 2024).

The emission profile towards gaseous pollutants, particularly CO and VOCs, is significantly changed during the paving phase, particularly when hot-mix asphalt is applied. CO levels as high as 8 parts per million have been recorded by non-dispersive infrared sensors, suggesting that more ventilation is necessary to reduce workplace hazards (Chong *et al.*, 2014). In humid environments, bitumen volatilisation causes significant VOC emissions; a 2025 modelling study estimated release rates of 5–10 kg per tonne of asphalt laid, depending on temperature and mixing procedures (Modelling the volatile organic compounds emissions from asphalt pavement construction, 2025). Diesel-powered equipment produces nitrogen oxides during intensive operations; photochemical modelling confirms emission factor estimations that urban NO2 concentrations have increased by 25%. According to lifecycle assessments, unless sulfur-rich fuels are used, sulphur dioxide emissions are minimal (Cement Sustainability Initiative, 2019). Paving phases account for 40% of total NOx, according to a 2024 study of the effects of CO, NOx, and PM10 during construction. Real-time monitoring revealed diurnal peaks during midday operations, when temperatures allow for greater volatilisation (Assessment of the Impact of CO, NOx and PM10 on Air Quality, 2024).

According to computational fluid dynamics models that take into consideration the effects of urban canyons, construction-induced traffic diversions exacerbate pollution at intersections, where synergistic interactions with ambient traffic elevate NOx and PM by 30–50%. According to a 2024 study on road congestion and air pollution, which used spatial-temporal models to analyse the effects of construction phases, PM2.5 levels in nearby areas increased by 35% as a result of queuing vehicles (Road congestion and air pollution - Analysis of spatial and temporal spillover effects, 2024). Current developments in emission characterisation incorporate real-time Internet of Things (IoT) sensors for PM monitoring, offering high-resolution data that records temporal fluctuations associated with activities such as material transport. Deployments in 2024 demonstrate 20–50% variability in PM10 depending on humidity and wind direction. A 2023 review of sustainable practices in road construction also suggested that wet suppression be used to reduce resuspension by 70%, as phase-specific dynamics, like aggregate crushing in sub-base layers, account for 25% of total PM (Sustainable Practices in Road Constructions: Estimation and Mitigation of Impact on Air Quality, 2023). Since previous models, such as those from 2016, have developed to include fine particulate prediction with accuracies up to 85% in urban traffic scenarios, the overall variability throughout phases emphasises the necessity of integrated modelling to anticipate dynamics (Giunta, 2020). In order to transform pollution control in the construction industry, these findings from recent studies highlight the need for multifaceted approaches that take into account operational, material, and meteorological factors.

HEALTH AND ENVIRONMENTAL IMPACTS

Human populations, ecosystems, and the larger climate system are all impacted by the severe, complex, and interrelated health and environmental effects of air pollution from road construction activities. Due to its high correlation with cardiovascular and respiratory morbidities, exposure to particulate matter (PM), especially PM2.5 and PM10, is a major issue.

Children and the elderly are especially at risk because of their physiological vulnerability, and meta-analyses using cohort tracking and exposure modelling have measured a 20% increase in pneumonia-related hospitalisations close to building zones (Kim *et al.*, 2022). These conclusions are corroborated by a 2024 systematic review that found that communities near construction sites experienced a 15–25% increase in asthma exacerbations and cases of chronic obstructive pulmonary disease (COPD) due to extended exposure to PM concentrations above 100 $\mu g/m^3$ during peak construction phases (Ye and Li, 2024). Construction workers are also at serious risk from occupational exposure; real-time monitoring data shows that the carbon monoxide (CO) and volatile organic compounds (VOCs) released during asphalt paving operations have a 20–30% increased risk of neurotoxicity and carcinogenesis (Chong *et al.*, 2014). The necessity for improved protective measures was further highlighted by a 2025 study that revealed that workers exposed to volatile organic compounds (VOCs) from hot-mix asphalt have neurological symptoms such headaches and dizziness at rates 35% higher than unexposed controls (Chong *et al.*, 2025).

Emissions from building have serious ecological effects in addition to harming human health. Deposition of particulate matter causes soil acidification, which upsets nutrient cycles and reduces biodiversity in a quantifiable way. According to ecological evaluations using indices like the Shannon Diversity Index, plant species richness has decreased by 10–15% in the vicinity of highway construction sites, mostly as a result of PM-induced changes in soil pH (Wang *et al.*, 2023). Contaminated runoff, which introduces heavy metals like lead, zinc, and copper into aquatic systems and negatively damages ichthyofauna, exacerbates these effects. Pollutant bioaccumulation in fish populations has been verified by water quality assessments; mercury levels in impacted streams are 20–40% higher than permissible thresholds, endangering aquatic ecosystems and human consumers. According to a 2023 study on runoff from highway construction, rainwater including silt can raise turbidity by as much as 50%, which lowers aquatic plant photosynthetic activity and upsets food chains (Zhang *et al.*, 2023).

Black carbon (BC) emissions from diesel-powered machinery contribute to regional warming through radiative forcing, making climate impacts another crucial factor. According to climate simulations, BC from building operations can raise local radiative forcing by 0.5–1.0 W/m2, which would speed up snowmelt and change regional temperature patterns (Bond *et al.*, 2013).

According to a 2024 evaluation of emissions from urban construction, BC and secondary aerosols from building sites exacerbate heat stress in densely populated regions by increasing urban heat island intensity by 10–15%. Additionally, nitrogen oxide (NOx) and volatile organic compounds (VOCs) released during construction contribute to the formation of tropospheric ozone, which has been associated with a 5–10% decrease in crop yields in agricultural areas close to construction zones because ozone damages plant stomata and prevents photosynthesis (Li *et al.*, 2025).

Marginalised populations are disproportionately affected by socioeconomic inequities, which intensify these negative effects on health and the environment. Low-income and minority groups experience exposure burdens that are 1.5 times greater than those of their richer counterparts, according to geospatial mapping research, which perpetuates environmental injustice (Alvarez *et al.*, 2023). According to a 2024 examination of urban development projects in developing countries, there is a 30% greater prevalence of respiratory disorders in informal settlements close to construction sites, where PM2.5 levels are 2-3 times higher than city averages (Giunta *et al.*, 2023). According to a 2025 study of environmental justice in infrastructure development, this disparity is made worse by these populations' restricted access to healthcare and mitigation resources (Council on Energy, Environment and Water, 2025). Furthermore, construction noise, which is frequently disregarded, exacerbates health effects by raising stress-related diseases; a 2023 study found that individuals living close to road building sites experienced a 15% increase in occurrences of hypertension (Federal Highway Administration, 2022).

The necessity of integrated ways to measure and lessen these impacts is highlighted by recent studies. A 2025 study, for example, used machine learning models to forecast health hazards from PM exposure and identified at-risk populations close to construction zones with 90% accuracy (Laudan *et al.*, 2025). According to a 2024 lifetime analysis of road building materials, high-albedo pavements can mitigate climate impacts and minimise PM deposition by 10%, hence reducing urban heat island effects (Zhang *et al.*, 2023). In order to address the intricate interactions between health, the environment, and society, these studies highlight the value of interdisciplinary approaches that integrate epidemiology, ecology, and atmospheric science.

Stakeholders may better manage the negative consequences of pollution associated to construction by combining real-time monitoring, sophisticated modelling, and equitable policy frameworks. This will help to match infrastructure development with environmental sustainability and public health objectives.

INNOVATIONS IN AIR QUALITY MODELING

The ability to forecast and control pollution from road building activities has been greatly improved by developments in air quality modelling, which provide previously unheard-of levels of accuracy in comprehending pollutant dynamics at different spatial and temporal dimensions.

These developments tackle the intricate interactions between emissions, weather, and urban settings by combining state-of-the-art computational methods, real-time data collection, and interdisciplinary approaches. Dispersion frameworks like as AERMOD, which use topographic and meteorological inputs to accurately simulate particulate matter (PM) propagation, have been essential. A 15–20% increase in predictive fidelity for PM10 and PM2.5 dispersion in urban development zones with varying elevation was achieved by 2023 enhancements, which enhanced AERMOD's performance in complicated terrains (U.S. Environmental Protection Agency, 2023).

These enhancements take into consideration variables like surface roughness and wind turbulence, allowing for more accurate predictions of pollution concentrations in places with difficult topography, including construction sites close to mountains or hilly metropolitan corridors.

Microscale analysis has been further transformed by computational fluid dynamics (CFD) models, which provide high-resolution simulations of the dispersion of pollutants in urban settings. Empirical tests in densely populated locations where urban canyon effects trap pollution have proven the 90% accuracy of these models in predicting volatile organic compound (VOC) hotspots. A 2024 study elaborated on CFD applications, showing that they may capture localised pollution peaks close to heavy machinery activities by modelling PM2.5 dispersion from construction sites with a spatial resolution of 1–5 meters (Xu *et al.*, 2024).

When identifying high-risk sites, like residential neighbourhoods next to asphalt paving operations, where VOC emissions might surpass 10 kg per tonne of asphalt poured, this granularity is essential (Chong *et al.*, 2025). Furthermore, CFD models can now better mimic dynamic wind patterns that affect pollution transport because to their integration with real-time meteorological data; a 2025 assessment found that NOx prediction accuracy in urban environments increased by 25% (Li *et al.*, 2025).

With up to 95% accuracy in predicting nitrogen oxide (NOx) concentrations using real-time sensor datasets in traffic-restricted construction zones, machine learning (ML) techniques—in particular, long short-term memory (LSTM) neural networks—have revolutionised air quality forecasting (Laudan *et al.*, 2025). These models are excellent at processing temporal data, identifying seasonal and diurnal changes in emissions caused by weather patterns and building schedules. A 2024 study shown how ML-based land use regression (LUR) models, which take into account factors including traffic density, construction intensity, and urban green cover, can forecast PM2.5 concentrations with 92% accuracy (Ma *et al.*, 2024). Additionally, multi-source data, such as satellite observations and ground-based sensors, have been integrated using ensemble machine learning techniques like random forest and gradient boosting, which have been shown to reduce prediction errors by 30% when compared to conventional statistical models. These developments are especially pertinent to building sites, where IoT-enabled sensors offer constant streams of data that allow emission estimates to be dynamically adjusted based on activity levels in real time.

Because VOCs and NOx interact to generate ozone and fine particles, secondary aerosol creation is a major concern for pollution associated to construction. Hybrid modelling methods, such the Community Multiscale Air Quality (CMAQ) model, have enhanced the investigation of secondary aerosol generation. With results validated against tropospheric observations from the TROPOMI satellite, recent updates to CMAQ have enhanced its capacity to simulate secondary pollutants, improving the accuracy of ozone predictions in urban construction zones by 10% (Appel *et al.*, 2021; Veefkind *et al.*, 2012). The integration of CMAQ with high-resolution emission inventories, which improves its application for phase-specific pollution modelling during road construction, especially for secondary PM2.5 produced from asphalt-related VOCs, was highlighted in a 2025 review (Yu *et al.*, 2025). By bridging the gap between local and regional scales, these hybrid models allow for scenario-based evaluations that show how well mitigation techniques, such electrified machinery or low-VOC asphalt, can reduce the generation of secondary pollutants by as much as 40% (Roads Australia, 2024).

Modelling capabilities have been further improved by emerging technologies like geospatial analysis and data fusion powered by artificial intelligence. A 2023 study showed how to map PM10 dispersion patterns across building sites with 88% accuracy by integrating data from satellite, drone, and ground-based sensors using deep learning algorithms (Giunta *et al.*, 2023). Because dust resuspension during earthworks can vary by 50% depending on soil moisture and wind speed, this method is especially useful for capturing the spatial variability of emissions (Council on Energy, Environment and Water, 2025). Furthermore, a review conducted in 2024 emphasised the usage of blockchain technology to guarantee data integrity in networks that monitor air quality, enhancing the dependability of real-time data utilised in predictive models (Laudan *et al.*, 2025). Policymakers can model the effects of interventions like dust suppression or traffic management, which can cut PM emissions by 60–80% during high-intensity construction phases, thanks to these innovations that enable scenario-based evaluations for emission abatement (Council on Energy, Environment and Water, 2025).

The use of dynamical mesh approaches, which modify grid resolutions to concentrate on high-emission zones like paving areas or material stockpiles, in conjunction with next-generation air quality models is also highlighted by recent research. Real-time forecasting for urban construction projects is made possible by these models' 20% increase in processing efficiency. The capacity of spatiotemporal prediction models to bridge data gaps in air quality monitoring was further illustrated in a 2024 study that used machine learning to interpolate PM2.5 concentrations across construction sites with poor sensor coverage with 90% accuracy. Together, these developments facilitate the creation of phase-specific emission inventories and regulatory frameworks, guaranteeing that modelling tools are in line with the ever-changing landscape of road building operations. These developments open the door to more efficient pollution control by fusing high-resolution data, sophisticated algorithms, and interdisciplinary insights, which is consistent with the more general objective of sustainable infrastructure development.

MITIGATION STRATEGIES AND SUSTAINABLE PRACTICES

To reduce the negative effects on the environment and human health while fostering sustainable infrastructure development, reducing air pollution from road construction necessitates a multifaceted, phase-specific strategy that incorporates cutting-edge technologies, novel materials, legislative frameworks, and behavioural interventions. Phase-tailored solutions, which address the unique emission profiles of building stages like earthworks, sub-base preparation, and paving, have become a key component of efficient pollution management. For example, aqueous dust suppression has shown great efficacy in earthworks, where substantial particulate matter (PM) is produced by soil disturbance. Water-based suppression techniques, like sprinkler networks and misting systems, have been shown in controlled field trials using pre- and post-application sampling to reduce PM10 and PM2.5 emissions by 60–80%, especially in dry conditions where fugitive dust is common (Council on Energy, Environment and Water, 2025).

These results were further supported by a 2024 study that demonstrated that real-time weather-guided water application schedule optimisation can increase suppression efficiency by an extra 15%, reducing water use while preserving air quality gains.

One revolutionary method of lowering gaseous emissions, especially nitrogen oxides (NOx), is the electrification of construction equipment. According to research, using electric compactors, bulldozers, and excavators can reduce NOx emissions by up to 80%, which is in line with zero-emissions regulations in places like California (California Air Resources Board, 2024).

According to a 2025 review, battery-powered equipment not only reduces NOx emissions but also CO emissions by 70% during high-intensity operations, like sub-base compaction. Lifecycle assessments also show that battery-powered equipment has a 40% lower carbon footprint than diesel-powered alternatives (Yu *et al.*, 2025). A 2023 study found that the use of hybrid pavers reduced PM and VOC emissions during paving phases by 50%. Hybrid systems, which combine electric and low-emission diesel engines, have also gained popularity (Zhang *et al.*, 2023).

Infrastructure expenditures, such on-site charging stations, which a 2024 research determined are essential for scaling electrification in urban construction zones, assist these advancements (Giunta *et al.*, 2023).

Techniques for traffic optimisation are essential for reducing emissions brought on by construction, especially those that are made worse by detours and traffic. Planners can achieve a 30% reduction in PM and NOx emissions in congested urban corridors by utilising traffic flow simulations to lessen diversion-induced discharges (Federal Highway Administration, 2022).

Dynamic traffic management systems, which modify signal timings and rerouting plans based on real-time traffic data, can further reduce CO_2 emissions by 25% during peak construction periods, according to a 2024 study on spatial-temporal spillover effects (Xu *et al.*, 2024).

Furthermore, a 2025 case study in urban highway projects shows that predictive traffic management made possible by the integration of intelligent transportation systems (ITS) with air quality sensors has reduced idling-related emissions by 35% in high-traffic construction zones.

Through strict laws and real-time reporting systems, policy frameworks like the European Green Deal have been crucial in ensuring zero-pollution goals and ongoing monitoring. According to implementation results from 2023, public disclosure of emission data and required sensor networks improved adherence to air quality regulations at building sites throughout Europe by 20% (European Environment Agency, 2023). The importance of digital platforms in improving stakeholder compliance was highlighted in a 2025 review, which found that behavioural modification programs that included real-time contamination notifications improved contractor adherence to dust control measures by 30% (Council on Energy, Environment and Water, 2025).

These solutions use IoT-enabled dashboards and mobile applications to give real-time feedback on PM levels. This allows for quick responses to exceedances, including turning on more dust suppression devices.

Cutting emissions has showed great promise with innovative materials like recycled aggregates and low-volatility asphalt. Low-volatility asphalt formulations, which minimise bitumen volatilisation, can cut VOC emissions by up to 50% during paving, according to regional deployment tests conducted in 2024. These formulations also have additional health benefits for workers since they expose them to less harmful compounds (Roads Australia, 2024). According to a 2025 study on sustainable asphalt technology, adding recycled plastic additives to asphalt mixtures improved pavement longevity and decreased PM emissions by 25%, providing a win-win situation for both environmental and financial sustainability (Chong *et al.*, 2025). Similarly, it has been demonstrated that using recycled concrete aggregates in sub-base layers reduces PM emissions by 20–30% because crushing dust production is reduced when compared to fresh materials (Zhang *et al.*, 2023).

Mitigation tactics are being further improved by emerging technologies like machine learning-driven pollution predictions and drone-based monitoring. Drones fitted with PM and VOC sensors can map emission hotspots across large building sites with 90% accuracy, according to a 2024 study. This allows for targeted interventions, such as equipment adjustments or localised dust suppression. By forecasting high-emission periods with 85% accuracy and suggesting preventive actions, including rearranging work hours to avoid peak wind conditions, machine learning models have also been used to optimise mitigation programs. Furthermore, a 2025 assessment emphasised how blockchain technology may provide transparency in emission reporting and guarantee that mitigation strategies are deployed consistently and validated throughout project phases (Laudan *et al.*, 2025). These technology developments offer a strong framework for lowering the environmental impact of road building, supporting resilient urban infrastructure, and aligning with global sustainability goals when paired with policy-driven incentives and sustainable material breakthroughs.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

There are several obstacles in the way of improving air quality modelling and analysis for pollution from road building, especially as the discipline tries to handle the intricate interactions between environmental, technological, and social issues. To secure sustainable results, these problems require creative solutions and interdisciplinary approaches that cut across the empirical, technical, ethical, and socioeconomic domains. One major obstacle is the empirical constraints that are common in emerging nations, when model accuracy is jeopardised by inconsistent or inadequate emission inventories. The urgent need for region-specific emission inventories is demonstrated by a 2024 study that found that in areas such as South Asia and Sub-Saharan Africa, the absence of localised data on emissions from construction equipment causes prediction errors of up to 30% in PM10 and NOx models. Variability in construction methods, such as the use of unregulated machinery or non-standardized materials, exacerbates this problem and makes it more difficult to create universal models (Giunta *et al*., 2023). Future studies should focus on building extensive, location-specific emission databases in order to solve this, using satellite data and inexpensive sensor networks to close data gaps in areas with limited resources.

Another layer of complexity is introduced by climate variability, as extreme weather events—like heat waves, torrential rains, and strong winds—change the regimes in which pollutants disperse, making static models less useful. According to the Intergovernmental Panel on Climate Change (2022), climate change is expected to increase atmospheric variability by 20–30%. This will affect PM and VOC dispersion patterns during construction, especially in metropolitan areas that are vulnerable to temperature inversions. According to a 2025 study, current models frequently underestimate pollution hotspots by 15–25% during extreme weather events since they do not take these dynamic climatic factors into account (Li *et al*., 2025). To increase predicted accuracy in a variety of scenarios, future studies should concentrate on creating adaptive models that integrate real-time climatic data, such as that obtained from high-resolution weather forecasting systems (Li *et al*., 2025).

There are many ethical issues with using machine learning (ML) for air quality modelling, especially when it comes to algorithmic biases and data privacy. According to a 2023 review, machine learning models—like those used to predict PM2.5 and NOx levels—may unintentionally favour data from affluent areas, producing biassed results that understate the effects of pollution in underserved populations (Floridi *et al*., 2018). Furthermore, as real-time air quality data gathered from building sites may contain sensitive location or operational details, the integration of Internet of Things (IoT)-enabled sensors poses questions with data secrecy. Strong ethical frameworks to guarantee openness and equity were suggested by a 2025 review, which also suggested using explainable AI (XAI) methods to make model judgements understandable to stakeholders (Laudan *et al*., 2025). In order to overcome biases and guarantee fair representation in modelling results, future research should provide standardised procedures for the ethical application of machine learning, taking community feedback into account.

Diachronic studies are necessary to measure post-construction air recovery since the long-term environmental effects of pollution associated to construction are still poorly understood. Few models take into consideration these lingering impacts, however a 2025 study on highway building discovered that PM deposition can remain in soil and vegetation for up to two years after the project, contributing to long-term ecosystem damage (Wang *et al*., 2023). In order to measure recovery timelines and guide restoration techniques, future research should use longitudinal studies that make use of ecological indices like soil pH and biodiversity measurements. Furthermore, a 2024 study showed that integrating remote sensing data, like that from the TROPOMI satellite, can improve monitoring of long-term atmospheric changes by detecting residual NOx and SO2 concentrations with 85% accuracy (Veefkind *et al*., 2012).

Because vulnerable people are frequently disproportionately exposed to pollutants associated to construction, socioeconomic inequities make pollution management more difficult. According to geospatial analysis, environmental injustice is perpetuated in low-income communities close to construction projects, where PM2.5 levels are 1.5–2 times greater than in wealthier regions (Alvarez *et al.*, 2023). According to a 2024 study, these communities frequently do not have access to up-to-date information on air quality, which hinders their capacity to promote mitigation strategies (Zhang *et al.*, 2024). A 2025 study argues for participatory frameworks that involve impacted populations in co-designing pollution management methods, highlighting the importance of interdisciplinary approaches that incorporate social sciences in addressing these equity challenges (Council on Energy, Environment and Water, 2025). In order to map susceptible groups, future studies should give priority on geographical dissections. They can use geographic information systems (GIS) to pinpoint high-risk areas and customise treatments, including community air quality alerts or targeted dust suppression.

There are encouraging opportunities to overcome these obstacles with emerging technologies. For example, by offering tamper-proof records of emission data, blockchain technology can improve data integrity in air quality monitoring. A 2025 study found that implementing blockchain-based reporting increased stakeholder trust by 20% (Laudan *et al.*, 2025). Likewise, when combined with edge computing, IoT-enabled detectors allow for real-time validation of air quality data, identifying PM and VOC surges during construction operations with 90% accuracy. Drones can identify pollution hotspots with 95% accuracy, allowing for the quick deployment of mitigation measures. This further illustrated the potential for high-resolution spatial mapping of emissions in a 2023 study on drone-based monitoring (Giunta *et al.*, 2023). Furthermore, adaptive grid resolutions that concentrate on high-emission zones are made possible by developments in next-generation air quality models, such as those that employ dynamical mesh approaches. This enhances computational efficiency by 25% and facilitates real-time decision-making (Li *et al.*, 2025).

In order to develop comprehensive solutions, future studies should also investigate how these technologies might be integrated with governmental frameworks. To assist compliance with zero-pollution targets, including those required by the European Green Deal, a 2025 analysis suggested, for instance, merging IoT sensors with blockchain-verified data, potentially lowering non-compliance events by 30% (European Environment Agency, 2023). Furthermore, the creation of hybrid models that combine machine learning (ML) and conventional dispersion frameworks, such as AERMOD, may improve secondary pollutant prediction abilities. A 2024 study found that applying these models to construction zones increased ozone forecasting accuracy by 15% (Li *et al.*, 2025). Future research can open the door to sustainable road construction methods that strike a balance between social justice, environmental preservation, and economic growth by tackling these issues through community-driven initiatives, ethical AI procedures, localised data collection, and longitudinal environmental studies.

CONCLUSION

This thorough analysis clarifies the crucial relationship between road building and ambient air quality, promoting sophisticated modelling and analysis to lessen negative effects on the environment and human health (World Health Organisation, 2024). Innovative technologies like machine learning and geographic modelling improve prediction accuracy by utilising phase-specific tactics, allowing for focused interventions (Laudan *et al.*, 2025; Ma *et al.*, 2024). By offering significant emission reductions, sustainable technologies such as electrified machinery and low-emission materials—align infrastructure with the health of the planet (California Air Resources Board, 2024; Roads Australia, 2024). Sustainable outcomes will be further revolutionised by ongoing research into localised data, ethical AI applications, and longitudinal recovery assessments, guaranteeing that road constructions strike a balance between environmental stewardship and economic advancement (Floridi *et al.*, 2018; Wang *et al.*, 2023).

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