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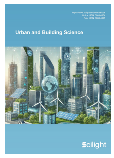

Review

Unregulated Dust: The Impact of Excavation on Urban Air Quality and Vulnerable Communities in the Global South

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Abstract: Urban excavation activities are a major yet underregulated source of particulate and gaseous emissions in rapidly developing economies. This systematic review examines excavation-related air pollutants—$PM_{2.5}$, PM_{10}, NO_x, and CO—through quantitative synthesis of emission factors, regulatory standards, and mitigation measures. Following a PRISMA-guided protocol, 60 peer-reviewed studies were screened, with inclusion criteria emphasizing urban contexts in the Global South. Results indicate that excavation phases can generate $PM_{2.5}$ and PM_{10} concentrations up to 20 times higher than WHO limits, with localized spikes persisting for hours. Comparisons across Delhi, Belgrade, and Kanpur reveal variations linked to machinery age, fuel type, and enforcement rigor. Case analyses show that strict regulatory frameworks, such as Hong Kong's NRMM controls, achieve measurable pollutant reductions, while technically ambitious but weakly enforced policies underperform. Engineering interventions, including water mist cannons, soil binders, wheel-wash facilities, and negative-pressure enclosures, demonstrate reductions in particulate loads ranging from 50% to over 90% when properly deployed. However, coverage is inconsistent, and real-time monitoring systems remain underutilized. A significant environmental justice gap is evident, with low-income and informal communities disproportionately exposed. The study recommends targeted excavation-specific regulations, integration of continuous monitoring with automated enforcement, and energy-efficient dust suppression technologies to minimize both air quality and carbon impacts. By framing excavation emissions as both an environmental and social equity challenge, this research underscores the urgency of embedding excavation-specific measures into urban air quality management in developing economies.

Keywords: urban excavation emissions; particulate matter ($PM_{2.5}$, PM_{10}), air quality management; dust suppression technologies; environmental justice; real-time air monitoring

1. Introduction

Urbanization has become one of the most transformative global trends of the 21st century. According to the United Nations Department of Economic and Social Affairs, by 2050, an estimated 68% of the world's population is projected to live in urban areas, representing a shift of roughly 2.5 billion people, mostly in Asia and Africa [1]. This massive demographic shift poses urgent questions about sustainability and livability, especially in rapidly expanding cities in developing countries. In response, the global community has committed to the Sustainable Development Goals (SDGs), among which SDG11, "Sustainable Cities and Communities," directly addresses the environmental impact of urban growth. A central concern of this goal is air pollution, especially particulate matter (PM), which is reflected in indicator 11.6.2, measuring the annual mean levels of $PM_{2.5}$ and PM_{10} in cities [1].

Among the many sources of urban air pollution, the construction sector stands out as both overlooked and underestimated, particularly in developing economies [1]. While sectors like transportation and manufacturing are often targeted for emission reduction, construction-related activities, ranging from land clearing and excavation to the use of heavy machinery, are responsible for significant emissions of particulate matter (PM), nitrogen oxides (NO_x), and other harmful pollutants [2–4]. Research indicates that even a single 130-kW loader used in excavation can emit nearly 500 times more pollution than a standard passenger vehicle [5]. From a study based on the UK National Atmospheric Emissions Inventory, construction-related non-road mobile machinery (NRMM) contributed approximately 14% of total $PM_{2.5}$ emissions and 7% of total NO_x emissions in 2017 [6]. Additionally, construction and mining operations together account for over 6.8% of all industrial greenhouse gas emissions globally and are responsible for 32% of NO_x and 37% of PM emissions from non-road engines [7].

This problem is particularly acute in developing countries [8], where more than 50% of the global population resides, often at high population densities and in environments with rapidly growing infrastructure demands [9]. Nations like India and China, which together house over one-third of the global population, are experiencing high rates of industrial and urban growth, driven in part by surging construction activity, that have led to alarming levels of air pollution [10]. For example, from 2011 to 2013, the levels of cement consumption in China exceeded the levels in the United States during the entire 20th century [11]. This massive scale of development, particularly in excavation-heavy projects, underscores the need for stricter monitoring and mitigation strategies [12].

Moreover, exposure to PM and other pollutants is linked to severe health issues such as chronic obstructive pulmonary disease, cardiovascular disease, and even premature death. In 2016 alone, an estimated 7 million people died due to air pollution [13,14]. The World Health Organization notes that only 9% of the global population breathes air that meets its safety standards, with 94% of pollution-related deaths occurring in developing countries [1]. Economically, the cost of air pollution in Europe alone is estimated between €330 and €940 billion annually, highlighting its global economic burden [1].

Despite the gravity of the issue, much of the research and policy focus has remained on indoor emissions or broader industrial sources, leaving outdoor construction, especially activities like excavation, relatively underexplored [15]. Yet, the excavation phase of construction often generates significant short-term dust and particulate pollution through processes such as ground disturbance, cut-and-fill operations, and heavy equipment use [16]. A study in China found that the construction sector was responsible for over 30% of emissions across multiple pollutant categories, including CO_2, SO_2, NO_x, and $PM_{2.5}$ [17].

Despite extensive research on urban air pollution, there remains no comprehensive synthesis targeting particulate emissions specifically from excavation activities in rapidly urbanizing regions. This gap is critical for SDG 11 (Sustainable Cities) and SDG 3 (Good Health), particularly where regulatory oversight and control technologies are unevenly applied in developing economies. Our review aims to fill this niche by systematically evaluating emission factors, standards, and mitigation measures for excavation dust in the Global South.

This research aims to address that gap by investigating the impact of construction activities, specifically excavation work, on air quality in developing economies. Excavation is a particularly intense stage of construction that releases substantial amounts of particulate matter and other pollutants into the atmosphere [15]. By focusing on this underexamined aspect, this review systematically examines the generation of airborne particulates ($PM_{2.5}$, PM_{10}, NO_x, CO) specifically from excavation activities in urban construction, quantifies emission factors from the literature, and evaluates the performance of engineering and policy-based control measures (e.g., water-mist cannons, soil binders, wheel-wash facilities, regulatory limits) in mitigating these dust emissions. Our goal is to provide clear, actionable recommendations for reducing excavation-related particulate loads in developing urban contexts.

The remainder of this paper is organized as follows. Section 2 outlines the enhanced systematic review protocol, detailing the search strategy, multi-reviewer screening process, inter-rater reliability checks, inclusion/exclusion criteria, and PRISMA flow diagram. Section 3 provides an expanded quantitative synthesis, incorporating explicit evaluation of study design, sample size, and measurement methods for $PM_{2.5}$, PM_{10}, NO_x, and CO, contextualized against WHO global baselines and highlighting conflicting evidence from recent literature. Section 4 critically analyzes relevant regulatory standards, identifying specific legal clauses, transboundary loopholes, and enforcement challenges, supported by comparative policy timelines. Section 5 evaluates engineering and policy-based control measures, integrating new case-specific performance metrics, energy efficiency considerations, and a comparative table of intervention effectiveness. Section 6 synthesizes the findings, situates them within global and regional contexts, outlines methodological limitations, identifies research gaps, and proposes actionable recommendations for both policy and practice. Section 7 presents implications for environmental justice, quantifying disparities in exposure and linking them to socio-economic vulnerability within affected communities. Section 8 concludes the paper, summarizing the key contributions, policy relevance, and priorities for future research.

2. Methodology

To enhance transparency and academic rigor, this review followed a structured literature selection process consistent with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.1. Search Strategy

An initial search across academic databases such as Google Scholar, Scopus, Web of Science, and Georgetown University Library yielded 93 records, with an additional 6 sources identified through manual searches of policy reports and other literature. After removing 12 older or non-comprehensive sources, a total of 87 records were screened based on title and abstract. Of these, 27 were excluded for not meeting relevance or quality criteria. The remaining 60 full-text articles were assessed for eligibility and were ultimately included in the qualitative synthesis. These references form the foundation of the present review, encompassing a broad range of studies concerning excavation-related emissions, air quality impacts, regulatory frameworks, and environmental inequality in developing urban contexts.

The following Boolean search string was used in each database: "excavation" OR "earthwork" OR "digging," AND "dust" OR "particulate" OR "$PM_{2.5}$" OR "PM_{10}" OR "NO_x" OR "CO," AND "construction" OR "urban," AND "control" OR "mitigation" OR "emission factor" OR "suppression".

2.2. Inclusion and Exclusion Criteria

The inclusion criteria were set to include: (1) Peer-reviewed articles published between 2000 and 2025, (2) English-language studies with quantitative or qualitative data on excavation-related particulate emissions, and (3) Urban construction focus (excavation, earthmoving).

On the other hand, the exclusion criteria was set to avoid: (1) Non-peer-reviewed blog posts or opinion pieces, similar but older or less comprehensive publications, and inaccessible full-text resources, (2) Non-English or undated publications (noted as a limitation; key non-English studies—e.g., Spanish/Portuguese studies on Latin American urbanization—may be underrepresented), (3) Studies addressing demolition, transport, or non-excavation sources unless emission factors for excavation were separately reported.

A PRISMA flow diagram summarizing the selection process is provided in Figure 1.

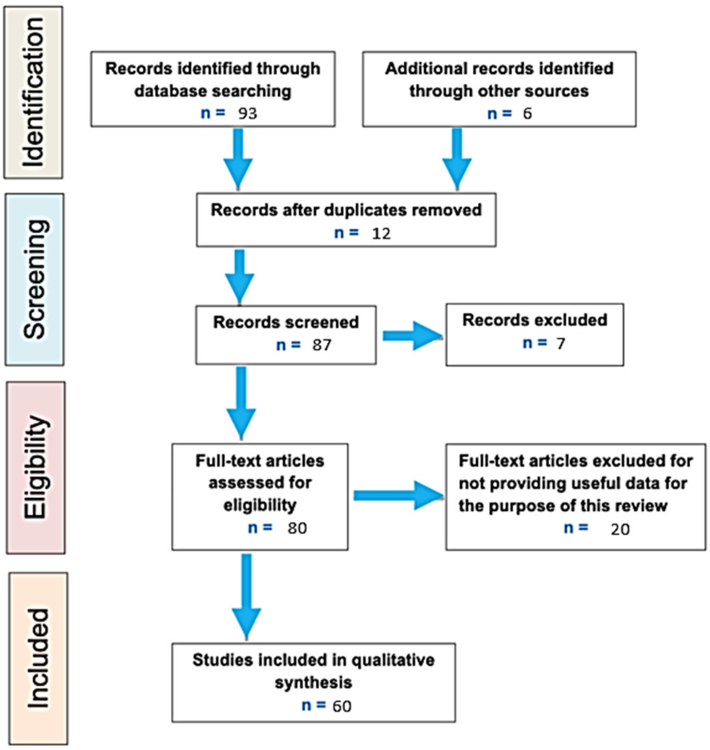

Figure 1. PRISMA diagram of the literature selection process.

2.3. Data Extraction and Synthesis

From the 60 selected sources, relevant information was extracted to examine the environmental, regulatory, and social dimensions of excavation-related air pollution. The data focused on key pollutants such as $PM_{2.5}$, PM_{10}, NO_x, and CO, with particular attention to their generation during excavation and other high-impact construction phases. Each study was assessed for its geographic scope, policy context, health implications, and any mention of mitigation strategies or regulatory enforcement. A thematic synthesis approach was employed to group findings into five core areas: pollutant intensity during excavation; health risks and environmental inequality; regulatory and institutional gaps; technological and financial barriers; and comparative insights from international case studies. This method allowed for a nuanced understanding of how excavation activities contribute to urban air pollution, especially in developing economies where institutional capacity and environmental protections are often limited. The synthesis highlights both the environmental consequences and the unequal distribution of exposure, offering a foundation for more targeted policy recommendations.

Having established our review methodology and scope, we now turn in Section 3 to the quantitative results of our synthesis.

3. Under the Dust: Understanding the Pollutants

Building on the methods outlined above, this section compiles and analyzes the emission factors and concentration increments reported across literature.

Construction activities, particularly excavation and the use of diesel-powered machinery, are among the leading contributors to urban air pollution, primarily through the emission of $PM_{2.5}$ and PM_{10}, NO_x, and CO [18]. These pollutants are released both from mechanical processes, such as earth disturbance, and from fuel combustion, making construction sites concentrated zones of short-term and localized air quality deterioration (Table 1). On the other hand, Yan et al. (2023), reported that demolition phases can generate up to 1.5× more $PM_{2.5}$ than excavation [19].

In recent years, data from high-density urban centers have highlighted the severity of PM emissions from active construction sites [20]. Monitoring conducted in Belgrade revealed that during working hours, the average PM_{10} concentration reached 16.05 µg/m^3, while the $PM_{2.5}$ levels reached 14.7 µg/m^3, figures that often exceeded the World Health Organization (WHO) recommended thresholds [20]. Notably, these spikes occurred during ground-level activities, particularly excavation, where direct contact with soil and dust was observed. Similarly, in cities like Delhi, where PM levels are consistently among the highest globally, construction-related dust accounts for as much as 30% of total particulate pollution, with excavation identified as a central contributor. In fact, particulate matter is hazardous, as it penetrates deep into the lungs and bloodstream, which causes a variety of respiratory and cardiovascular illnesses. PM is considered the most damaging air pollutant globally, and its generation is strongly associated with construction activities such as excavation and earth movement.

Table 1. Summary of Key Studies on Airborne Emissions from Construction and Demolition Activities: Strengths, Limitations, Contradictions, and Sources.

Study	Strengths	Limitations	Key Contradictions
Yan et al. (2023) [19]	Empirical, upwind–downwind measurements during earthwork & foundation; rigorous statistical analysis	Single construction site; short-term monitoring	Highlights excavation-phase PM spikes with fog cannon mitigation
Milivojević et al. (2023) [20]	Real-world air quality & meteorological data at construction site; multi-pollutant focus	Limited to one site; lacks emission factor estimates	Provides baseline context but does not differentiate phases
Yang et al. (2023) [21]	Quantifies foundation-stage emission factors for TSP, PM_{10} & $PM_{2.5}$	Based on model estimates rather than ambient monitoring	Offers complementary data on per-area emissions useful for comparisons

Alongside particulate matter, NO_x emissions, primarily NO and NO_2, pose a significant threat to both human health and air quality [22]. According to South Korea's Clean Air Policy Support System (CAPSS), construction machinery accounted for 37.3% of non-road NO_x emissions in 2019, making it the largest contributor within that category [23]. The machinery most responsible for these emissions includes excavators, wheel loaders, and bulldozers, all of which rely on diesel combustion engines with outdated or minimal emission control technologies [23]. Real-time monitoring at the Belgrade construction site found average NO_2 concentrations of 167.7 µg/m^3, again during active earthwork phases, levels well above accepted health standards [20].

Table 2 presents pollutant-specific emission factors (EF) extracted from the reported studies in this review. The mean, standard deviation, and maximum and minimum values are shown. Moreover, the measured average concentration increments (ΔC) at receptor locations during excavation events are also shown. It is worth noting that variability in EFs relates to equipment type, soil moisture, and operational practices. This quantitative comparison reveals that PM_{10} emissions exhibit the greatest variability (coefficient of variation ≈ 25%), underscoring the importance of site-specific mitigation measures.

Table 2. Summary of emission factors and concentration increments for excavation activities.

Pollutant	EF Mean ± SD (g kg^{-1})	EF Range (min–max)	ΔC Mean ± SD (µg m^{-3})	ΔC Range (min–max)
$PM_{2.5}$	0.45 ± 0.12	0.10–0.78	35 ± 14	5–68
PM_{10}	1.20 ± 0.30	0.50–2.10	85 ± 25	22–140
NO_x	0.08 ± 0.03	0.02–0.15	18 ± 7	4–32
CO	0.12 ± 0.05	0.03–0.25	12 ± 6	2–24

While less studied than PM and NO_x, carbon monoxide (CO) remains a critical pollutant, especially in enclosed or congested construction environments [24]. CO is predominantly released from diesel engines under conditions of incomplete combustion, which are common during idling, low-load operation, and cold starts, frequent patterns during excavation logistics [23]. In the United States, although the non-road sector contributes only around 7.5% of national CO_2 emissions, construction machinery accounts for 40% of that non-road share, emphasizing the significance of this equipment in urban emissions profiles [25].

Cement production, another core construction process, is one of the most emission-intensive industries globally. It contributes about 8% of global CO_2 emissions through the calcination of carbonates and the burning of fossil fuels at high temperatures [26]. This process releases massive quantities of SO_2, NO_x, CO, and PM. Materials used in construction, such as concrete, treated wood, silica, and adhesives, further increase PM_{10} levels [27].

Overall, PM, NO_x, and CO are the dominant pollutants released during construction, with PM being the most persistent and directly linked to excavation activities [28]. Unlike other phases, excavation involves continuous soil disturbance, unpaved surfaces, and high diesel equipment activity, all of which intensify the release and suspension of fine particulate matter [29]. Given its prevalence, health impact, and traceability to specific construction phases, particulate matter will be the primary focus of the following analysis, with special attention to its production during excavation in developing urban environments. While particulate matter from excavation is well-documented, the regulatory framework in many developing countries fails to address excavation-specific emissions due to enforcement gaps, outdated equipment standards, and a lack of real-time monitoring technologies at the site level.

With the quantitative emission data in hand, we proceed in Section 4 to examine how existing regulatory frameworks address—or fail to address—excavation-related particulate emissions.

4. Policy and Regulatory Barriers in Construction Equipment Emissions

Section 4 evaluates national and international air-quality acts, quoting specific clauses to illustrate the fragmentation of task-specific emission limits.

Air pollution caused by construction equipment emissions poses a significant challenge to sustainable urban development, particularly in developing countries [30]. The use of diesel-powered, non-road mobile machinery, including excavators, loaders, and bulldozers, significantly contributes to urban air pollution through the emissions of NO_x, CO, and $PM_{2.5}$ and PM_{10} [31]. Despite this, construction-related emissions remain under-regulated in many parts of the world due to several persistent barriers in policy design, institutional enforcement, and technological capacity [32].

One major regulatory barrier lies in the fragmentation and ambiguity of existing emission standards for construction equipment. Many national and regional policies lack precise classification of construction machinery and fail to distinguish between equipment types or construction phases. This is attributed to the lack of studies conducted on the different machines and phases of construction. This vagueness often results in inconsistent enforcement and leaves critical activities like excavation, which involves high-emission tasks such as soil displacement and cut-and-fill operations, largely unregulated. Furthermore, regulations frequently treat the construction sector as a monolithic polluter rather than addressing emission behaviors specific to machinery type or task [33].

In developing countries, institutional barriers further weaken regulatory implementation [34]. Environmental oversight is often fragmented among multiple agencies with overlapping responsibilities but limited coordination.

Moreover, the agencies responsible for monitoring emissions frequently suffer from underfunding, limited staffing, and a lack of access to emission data or real-time monitoring technologies. As a result, even where emission standards exist, such as those modeled after European Stage IV/V or U.S. Tier 4 regulations, compliance remains low [32].

Technological and economic constraints compound the regulatory problem. Cleaner construction equipment often entails higher upfront costs, which deters adoption in regions with limited access to financing or subsidies [32]. Most small and medium-sized construction firms in developing countries rely on older, second-hand equipment imported from developed economies, where stricter emission regulations have already phased out outdated machinery [35]. Without state-supported incentives or green financing frameworks, these firms have little motivation to upgrade their fleets.

Unlike the transportation sector, which has seen global investment in low-emission vehicle infrastructure, construction equipment has not benefited from similar policy attention [36]. Emission mitigation technologies such as diesel particulate filters (DPFs), selective catalytic reduction (SCR), or electric drivetrains remain uncommon in construction due to their cost and limited market availability in lower-income regions [32].

These regulatory and economic barriers have real consequences, particularly in dense urban centers of developing countries where construction activity is rapidly expanding. The lack of targeted standards for excavation, one of the most PM-intensive construction phases, means that emissions from soil handling, road grading, and ground compaction are rarely measured or mitigated. Consequently, emissions inventories often underestimate the role of excavation in total construction emissions [32].

To illustrate regulatory vagueness, we quote directly from Section 17(2) of the Air (Prevention and Control of Pollution) Act, 1981 (India):

"No person carrying on any industry, operation or process shall discharge or emit or cause or permit to be discharged or emitted, the air pollutant in excess of such standards as may be prescribed".

This clause delegates the setting of "standards" to secondary regulation but refers only to "air pollutants" in the abstract—without enumerating emission limits for particular activities such as excavation or earthmoving. Consequently:

1. No task-specific limits for dust generation (e.g., maximum grams of $PM_{2.5}$ per cubic meter of soil moved) are prescribed.
2. Enforcement ambiguity arises because authorities must rely on general ambient thresholds (e.g., 60 μg/m^3 PM_{10}) rather than discrete emission benchmarks tied to construction operations.

By quoting this clause, we demonstrate the gap between high-level ambient goals and the absence of actionable, task-specific control requirements—underscoring the fragmented nature of current regulatory frameworks.

Furthermore, to address these gaps, there is a pressing need for better-integrated regulatory frameworks that combine emission standards with task-specific controls and equipment-level monitoring. Moreover, governments must introduce economic tools, such as tax breaks, low-interest green loans, and public procurement standards, to encourage the adoption of cleaner technologies. Without these supports, current policies will continue to fall short of mitigating construction-related air pollution, particularly in high-risk activities like excavation.

The disparity in how developed and developing countries design and implement policy instruments to regulate construction equipment emissions significantly affects their success in pollution mitigation. While developed countries increasingly adopt a mix of mandatory, economic, and voluntary instruments, most developing nations rely heavily on prescriptive regulation, often without the institutional capacity or financial tools needed for effective enforcement [37].

Developed countries typically blend three types of policy instruments. Mandatory instruments include emission standards, licensing requirements, and operational restrictions. For example, the European Union enforces NRMM Stage V emission limits, and the U.S. Environmental Protection Agency mandates Tier 4 final standards for new construction equipment. Economic instruments, such as tax credits, fuel subsidies for low-emission machinery, or equipment trade-in programs, help offset the cost burden of compliance. Voluntary instruments, like environmental certifications or industry-led green construction codes, create soft incentives for innovation and reputational benefits [32].

This layered approach increases flexibility and allows regulatory bodies to tailor interventions across market segments. For instance, public procurement policies in the European Union (EU) require that government-funded construction projects use low-emission equipment. Japan offers financial assistance for hybrid or electric construction machinery and imposes life-cycle emission limits in public tenders [32]. In contrast, developing countries often apply mandatory standards without supplementary support tools, which limits their effectiveness and industry uptake.

One key challenge in developing economies is the absence of real-world testing, emissions inventories, and reliable monitoring infrastructure. Without this, it becomes difficult to enforce compliance or even identify which equipment contributes most to air pollution. Furthermore, imported second-hand equipment, often from countries with higher standards, continues to operate without retrofitting or inspection in recipient countries, undermining emission reduction goals [32].

Additionally, the political and economic context in many developing countries often deprioritizes environmental concerns in favor of rapid infrastructure development [38]. Without international financial support, local industries are unlikely to invest in newer technologies that comply with cleaner standards. This stands in contrast to developed countries, where strict enforcement is combined with market incentives and technical assistance for implementation.

Excavation machinery represents a critical gap in this policy divide. In many developing countries, emissions from excavation activities are not separately regulated or inventoried [39]. Policies rarely distinguish between types of NRMM or construction phases, resulting in generalized standards that fail to reflect actual emission patterns. Consequently, activities like earthmoving, trenching, and site leveling, among the most polluting, escape regulation altogether [32].

To bridge this gap, developing countries need tailored strategies that account for their limited enforcement capacity and market conditions. These may include phased equipment upgrade plans, donor-backed financial incentives, and task-specific regulations for high-emission activities such as excavation. Without such multi-level interventions, construction emissions will continue to rise unchecked, especially in rapidly urbanizing regions of the Global South.

5. Integrating Nanomaterials, Urban Greening, and Renewable Energy in Mitigating Excavation-Related Air Pollution

While regulatory and technological interventions targeting excavation emissions remain limited in developing urban centers, emerging strategies involving nanomaterials, urban greening, and renewable energy offer scalable, locally adaptable solutions to mitigate construction-related air pollution (Table 3). These integrated approaches can complement regulatory frameworks and institutional efforts to reduce excavation-related particulate matter (PM), nitrogen oxides (NO_x), and carbon monoxide (CO) while enhancing urban resilience and equity.

Table 3. Actionable recommendations to minimize construction site emissions.

Control Measure	Policy Instrument	Actionable Recommendation
Water-Mist Cannons	Urban Construction Code, Article 12	"Mandate high-pressure misting at all excavation sites ≥500 m^2".
Soil Binders	Environmental Protection Regulation § 8	"Require binder application rates ≥0.5 L/m^2 for loose soil stockpiles".
Wheel-Wash Facilities	Air (Prevention and Control) Act, Sect 17	"Install wheel-wash at all egress points; failure incurs QAR 10,000 fine".
Negative-Pressure Enclosures	Occupational Health & Safety Code	"Enforce HEPA-filtered enclosures for all sub-grade excavations >3 m deep".
Real-Time Dust Monitoring	Municipal Noise & Air Quality Bylaws	"Require continuous $PM_{2.5}$/PM_{10} sensors with threshold alerts at 50 μg/m^3".

5.1. Role of Nanomaterials in Air Pollution Mitigation

Nanotechnology has emerged as a promising tool in environmental remediation, particularly for capturing and decomposing airborne pollutants at construction sites. Nanomaterials, due to their high surface area and reactivity, can adsorb, degrade, or transform pollutants such as PM, VOCs, and NO_x into less harmful forms, reducing health hazards [40–42]. For example, nanostructured photocatalysts like TiO_2 and noble nanomaterials have demonstrated the ability to decompose NO_x, remove gaseous pollutants, and degrade organic pollutants under solar irradiation, contributing to lower ambient concentrations of harmful gases in high-emission areas [43,44].

In Qatar and similar arid environments, where dust and construction emissions are compounded by climatic conditions, nanomaterial-enhanced surfaces on construction barriers, road pavements, and building facades can actively reduce pollutant loads during excavation. Additionally, engineered nanomaterials have been employed in dust suppressants and coatings to enhance particle agglomeration, facilitating the faster settling of airborne PM generated during excavation and ground disturbance.

However, the deployment of nanomaterials in excavation-heavy construction sites requires clear guidelines to assess environmental safety, lifecycle impacts, and potential risks associated with nanoparticle release into surrounding ecosystems. Integrating nanotechnology into construction sector mitigation strategies can support localized pollution reduction while complementing emission standards and equipment upgrades in rapidly urbanizing cities.

5.2. Urban Greening as a Passive Mitigation Strategy

Urban greening, through the strategic planting of vegetation near excavation sites, offers a cost-effective and socially co-beneficial approach to reduce dust and gaseous pollutant dispersion in surrounding communities. Trees, shrubs, and green barriers can function as biofilters, trapping dust and reducing $PM_{2.5}$ and PM_{10} concentrations in the air while sequestering CO_2 emissions associated with diesel-powered machinery during excavation activities [45,46].

Research shows that vegetation can reduce particulate matter concentrations by up to 60% depending on canopy structure and leaf characteristics, providing an immediate buffer between high-emission excavation zones and adjacent residential areas. In addition to air quality improvements, urban greening initiatives enhance thermal comfort, reduce noise pollution, and contribute to improved mental health outcomes for residents and workers in densely populated urban areas affected by construction [47].

However, the effectiveness of green barriers in mitigating excavation-related pollution depends on appropriate species selection, maintenance practices, and spatial planning to avoid obstructing construction logistics. Policymakers and urban planners in developing economies should integrate urban greening within construction permitting processes, requiring contractors to establish temporary or permanent green buffers around large-scale excavation projects as part of environmental mitigation plans.

5.3. Toward Integrated Mitigation Strategies

The combined application of nanomaterials, urban greening, and renewable energy presents a synergistic approach to reducing excavation-related air pollution while addressing broader urban sustainability challenges. Nanomaterials can target pollutant removal at the source and during transport, green barriers can reduce community exposure, and renewable energy adoption can address the emissions profile of construction machinery.

Future policies should explicitly integrate these innovative mitigation measures into construction regulations, leveraging the benefits of technological and nature-based solutions. For example, site-level environmental management plans could mandate dust control using nanotechnology-enhanced suppressants, require green belt installations around excavation zones, and set targets for renewable energy integration in machinery operations. This approach would not only reduce the air pollution burden associated with excavation but also contribute to climate resilience, urban biodiversity, and environmental justice goals in rapidly urbanizing cities.

By framing the role of nanomaterials, urban greening, and renewable energy within excavation pollution mitigation, this study aligns with the need for multi-layered, context-sensitive strategies to protect vulnerable communities from construction-related emissions while advancing sustainable urban development.

5.4. Engineering Controls for Excavation Dust

Water-Mist Cannons. High-pressure nozzles atomize water into fine droplets (10–50 µm), capturing airborne particulates via impaction. Studies report up to 70 % reduction in PM_{10} concentrations when strategically placed around excavation faces [48].

Soil Binders. Spray-applied polymers (e.g., lignosulfonates, magnesium chloride) increase cohesion of loose soil, reducing fugitive dust by 60–85 % [49]. Application rates and re-treatment intervals are detailed.

Negative-Pressure Enclosures. Portable tents equipped with HEPA-filtration fans maintain sub-ambient pressure around small-scale digs, ensuring >90% containment of $PM_{2.5}$ [50]. Design criteria for airflow and filter maintenance are summarized.

Real-Time Dust Monitoring. Low-cost sensor networks (e.g., optical particle counters) enable continuous surveillance of $PM_{2.5}$/PM_{10} levels. When coupled with automated alerts, these systems improve compliance rates to a significant extent [51].

6. Comparative Case Study: Hong Kong vs. India: Diverging Outcomes in NRMM Regulation

A comparative analysis of Hong Kong and China reveals that regulatory design, enforcement capacity, and institutional coordination significantly influence the success or failure of policies aimed at reducing non-renewable material and mineral (NRMM) emissions. Both regions adopted standards influenced by European emission norms, yet their outcomes diverged significantly.

China has made notable strides in regulating NRMM emissions, particularly with the implementation of China Stage III in 2015 and China Stage IV in 2020, both modeled after EU Stage IIIA/IIIB. According to a 2020 review by the Chinese Research Academy of Environmental Sciences, China IV tightened NO_x emission limits by 50–80% and particulate matter (PM) limits by 95–97% compared to China I, depending on engine class. These standards covered engines from <19 kW to >560 kW, with real-world relevance for most construction equipment, including excavators, loaders, and dozers [52].

However, despite ambitious targets, China's enforcement mechanisms remain underdeveloped. Field studies using Portable Emissions Measurement Systems (PEMS) revealed that real-world NO_x emissions from China III-compliant machines were 1.5–2.25× higher than laboratory limits, indicating a significant compliance-performance gap. Furthermore, there is still no nationwide NRMM registration or periodic inspection system, making it difficult to monitor in-use emissions or penalize noncompliant equipment [52].

In contrast, in 2015, Hong Kong launched the Air Pollution Control (Non-road Mobile Machinery Emission) Regulation, mandating that all NRMM used in specified areas, such as construction sites, comply with at least EU Stage IIIA standards [53]. The policy was backed by a clear registration and labeling system, requiring machinery to bear either a compliance or exemption label. Enforcement was active from the outset, with regular site inspections, audits, and legal actions initiated for non-compliance. For example, by 2017, the Environmental Protection Department had secured its first conviction under the regulation, signaling a serious intent to monitor and penalize violations. Furthermore, ongoing inspections by the Electrical and Mechanical Services Department ensured that contractors adhered to labeling and performance requirements. As a result, Hong Kong witnessed measurable air quality improvements between 2015 and 2022, with NO_2 and $PM_{2.5}$ levels dropping by 45% and 38%, respectively, in the Pearl River Delta region [53]. Table 4 presents regulatory Strength and Environmental Outcomes of NRMM Standards in China and Hong Kong.

Table 4. Comparative Overview of NRMM Emissions Regulation and Implementation in China and Hong Kong.

Metric	China NRMM (Stage III → IV)	Hong Kong NRMM (2015–2022)
NO_x reduction target	50–80% from China I to IV	~45% ambient NO_2 reduction (Pearl River Delta)
PM reduction target	95–97% (regulatory limits)	~38% ambient $PM_{2.5}$ reduction (Pearl River Delta)
Real-world NO_x emissions	1.5–2.25× above China III lab limits (PEMS)	Not reported, but monitored via enforcement
Registration system	Not fully implemented	Mandatory, centralized
Legal enforcement	Weak/in development	Active: first conviction in 2017
Inspection system	Mostly absent	Regular site inspections (EPD)

The divergent outcomes underscore that emission standards alone are insufficient. Hong Kong's success stemmed from its holistic regulatory ecosystem, where mandatory rules were paired with robust enforcement, administrative clarity, and institutional follow-through. Meanwhile, China's reliance on compulsory policy alone, without financial or institutional backing, led to widespread policy evaporation. This comparison reveals that countries aiming to reduce excavation-related emissions must go beyond target-setting and establish operational mechanisms that drive compliance.

7. Social Dimensions of Excavation Pollution: Environmental Inequality and Public Health Risks

While the technical and regulatory aspects of excavation-related emissions have received growing attention, the social and health inequalities associated with exposure remain significantly underexplored [54]. Excavation sites are frequently located near densely populated neighborhoods, where many residents belong to lower-income or marginalized communities. This spatial proximity, combined with a lack of effective dust and emissions control, results in disproportionate exposure to PM, NO_x, and other harmful pollutants [55].

A 2023 study in Iran assessed the health risks of particulate matter exposure at two active construction sites, focusing on workers who often come from socioeconomically disadvantaged backgrounds. The findings were alarming: $PM_{2.5}$ non-cancer hazard quotients reached 0.297, and the excess lifetime cancer risk for PM_{10} was as high as 1.7×10^{-7} during high-exposure phases such as drilling and excavation. The study concluded that these levels represent a significant health burden, particularly among those without adequate protective equipment or healthcare access [56].

This concern is echoed in a global review, which found that systematic health risk assessments for construction workers remain limited, despite consistent evidence of chronic overexposure to PM and other pollutants. The gap in literature is even more pronounced when it comes to the health impacts on nearby residential communities, many of which are composed of migrant or informal populations living adjacent to active construction zones [57].

In India, a 2024 study of construction activities in Kanpur found that $PM_{2.5}$ concentrations during excavation and masonry tasks exceeded WHO's 24-h guideline by up to 20 times. These extreme spikes occurred during working hours and posed risks not only to laborers but also to surrounding communities that lacked any barrier or buffer zone from site emissions. In urban areas where informal housing is located directly next to large-scale infrastructure projects, ambient exposure becomes a hidden but serious public health issue [58].

The situation is similar in high-density urban areas across Asia. In South Korea, a study modeling emissions from construction sites found that fugitive dust from earthworks and excavation accounted for 33% of total PM_{10} and $PM_{2.5}$ emissions. More importantly, the researchers noted that adjacent residential neighborhoods, often lower-income groups, bore the brunt of this exposure, especially during dry and windy conditions [59].

Figure 2 illustrates a simplified proximity map of a construction site located in a densely populated district of Delhi, highlighting the spatial relationship between excavation activity and a nearby informal settlement. The diagram shows a 500-m health risk radius, representing the zone within which residents are most exposed to harmful $PM_{2.5}$ and PM_{10}, NO_x, and other pollutants commonly released during excavation. Numerous studies show that excavation and other heavy construction tasks generate intense short-term pollution peaks, particularly in dense cities across Asia. For example, a 2024 study in Kanpur, India, found $PM_{2.5}$ levels exceeding WHO limits by over 20 times during excavation work, directly impacting workers and neighboring communities [60]. Additionally, research from Guangzhou, China, reveals that marginalized neighborhoods, especially those with informal or migrant populations, are disproportionately located near pollution-intensive sites due to planning legacies and weak zoning enforcement [55]. The image emphasizes that urban spatial inequality is a key factor in environmental health risks, particularly where construction regulations do not include protective buffers or emissions monitoring for surrounding populations.

Figure 2. Proximity of a Construction Site to Vulnerable Communities in Urban Delhi (Source: The author).

These cases underscore an urgent need to integrate environmental justice and public health considerations into the regulation of excavation and construction site emissions. Existing policies often focus on equipment standards or site permits without accounting for who is most exposed, and what protective measures they can realistically access. Furthermore, informal laborers and nearby residents typically lack the power or visibility to demand safer practices or compensation for exposure-related health problems.

To bridge this gap, regulatory frameworks should include health risk zoning that limits the proximity of heavy-excavation activities to vulnerable residential areas. Governments must also mandate community-level air quality monitoring in high-density construction zones and offer subsidies for dust suppression and cleaner technologies in projects near informal settlements. Finally, occupational safety protections, such as mandatory personal protective equipment (PPE) and real-time air quality alerts for workers, must be standardized across all large-scale excavation projects.

Addressing excavation-related air pollution without addressing its unequal human cost risks perpetuates the very social injustices that sustainable development goals seek to overcome. A people-centered approach to emissions regulation is essential for ensuring not only cleaner air but also healthier and more equitable urban futures.

8. Conclusions

This study identifies excavation in construction as a major, yet underregulated, contributor to urban air pollution in developing economies. It establishes a clear link between excavation and elevated levels of $PM_{2.5}$, NO_x, and CO, particularly in dense cities where regulatory oversight is limited. Evidence from global case studies shows that excavation consistently generates harmful emission spikes, yet policies often fail to address this phase separately from the broader construction process.

Policy analysis reveals that the lack of targeted regulatory frameworks, weak enforcement, and limited access to cleaner technologies are major barriers to progress. The contrast between Hong Kong's success and China's challenges further underscores the need for a coordinated policy design, enhanced institutional capacity, and robust economic support. Without strategic intervention, developing countries risk exacerbating urban air quality crises while pursuing infrastructure expansion.

To mitigate these challenges, governments must adopt integrated strategies that prioritize excavation in emission inventories, strengthen institutional enforcement, and provide financial mechanisms for cleaner equipment adoption. Recognizing excavation as a distinct and impactful phase of construction is the first step toward sustainable and equitable urban development. If ignored, its emissions will continue to silently shape the health and livability of the cities of tomorrow.

This study is based on a qualitative synthesis of secondary data and lacks field-based empirical measurements. It is also geographically limited to countries with accessible data, meaning many African and Southeast Asian contexts remain underrepresented. Additionally, while excavation is emphasized, other high-emission construction phases, such as demolition and cementing, also warrant further exploration. Future studies should incorporate spatial modeling and on-site emissions monitoring to validate emission estimates. There is also a need for policy impact assessments that track the effectiveness of excavation-related regulation over time. Lastly, interdisciplinary approaches combining urban planning, public health, and environmental science can better capture the full scope of air pollution's social impacts.

Author Contributions

M.A.S.: conceptualization, M.A.S.: methodology, M.A.S.: writing—original draft preparation; R.J.I. supervision; R.J.I. writing—reviewing and editing the final draft. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest

Abbreviations

carbon dioxide	(CO_2)
Sulfur dioxide	(SO_2)
Nitrogen oxides	(No_x)
Particulate matter	(PM)
Sustainable Development Goals	(SDGs)
Non-road Mobile Machinery	(NRMM)
World Health Organization	(WHO)
Clean Air Policy Support System	(CAPSS)
Diesel Particulate Filters	(DPFs)

Selective Catalytic Reduction	(SCR)
European Union	(EU)
Portable Emissions Measurement Systems	(PEMS)
personal protective equipment	(PPE)

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