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A Structured Review and Classification of Environmental Pollution Factors at High-Rise Construction Sites

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Abstract

Rapid urbanization and the rise of high-rise construction projects have intensified environmental challenges, making pollution control a critical concern for sustainable development. This study aims to systematically identify and classify pollution factors at high-rise construction sites, focusing on the Vietnamese context. A structured literature review was conducted, based on 125 publications retrieved from Web of Science, Scopus, ScienceDirect, and Google Scholar. After screening for relevance and quality, 32 studies were selected for detailed content analysis and frequency analysis of pollution factors. Findings show two categories of factors: direct factors, including construction processes, machinery, equipment, and transportation, and on-site human activities; and indirect factors, encompassing management and people, material management, and environmental and external factors across four pollution categories: air, noise, water and solid waste. A frequency matrix was developed to map how often each factor was linked to different pollution types. Key hotspots identified include material and waste haulage (34.4%), earthworks (31.3%), and machinery operation (31.3%), which collectively dominate air and noise pollution across the reviewed studies. Construction wastewater and runoff (21.9%) are the leading contributors to water pollution. In contrast, design errors (25%) and weak workforce skills (21.9%) were the dominant drivers of solid waste. Based on these results, three strategic directions are proposed: (i) source control and immediate mitigation for mechanized activities and point-source discharges; (ii) upstream prevention through improved design, planning, and material management; and (iii) enhancement of human resources and stakeholder environmental awareness. The study identifies the pollution factors associated with construction activities and emphasizes the necessity for integrated strategies to ensure sustainable urban growth.

1. Introduction

The construction industry is a fundamental driver of Vietnam's economic development. The industry and construction sector recorded a GDP growth rate of 8.24% and accounts for 37.64% of Vietnam's economic structure [1]. Driven by rapid urbanization, with 38.1% of the population now residing in urban areas [2]. This trend has intensified demand for housing and infrastructure, leading to a surge in high-rise building projects. It was found that the floor area of apartment buildings with 26 or more floors rose by 9.1% on average per year, reaching 690,800 m^2. This was the biggest rate of growth for any type of apartment building [3]. However, this rapid growth has created substantial environmental risks. The construction sector is responsible for 23% of air pollution, 24% of greenhouse gas emissions, nearly 50% of natural resource consumption, and 40% of drinking water contamination[4]. Activities like demolition and the operation of heavy machinery generate dust and emissions that seriously affect local air quality [5]. These impacts highlight the urgent need for pollution control measures. The impact of environmental pollution are diverse and interrelated. For instance, dust affects both air quality and surface water. Beyond health risks, adverse conditions reduce labor productivity and cause delays[6–8], while environmental incidents may lead to project suspension and financial losses.

High-rise construction projects intensify environmental impacts by concentrating materials, machinery, and labor in confined spaces. Deep excavation and vertical material transport generate more dust, noise, waste, and emissions than low-rise projects, potentially producing greater lifecycle carbon emissions[9]. Definitions of "high-rise" vary globally, ranging from over 23 meters in the US[10], to specific height categories in China [11]; however, Vietnam's TCVN 9363:2012 defines high-rises as buildings between 9 and 40 stories[12]. These large-scale, complex techniques, significant material demand, and heavy machinery consistently magnify their environmental impacts. Therefore, adopting effective control measures is urgent, positioning the environmental aspect as a primary pillar of sustainable construction [13].

Vietnam addresses these challenges through a comprehensive legal framework, including the 2020 Law on Environmental Protection and Decree 16/2022/ND-CP, which mandates EIAs and penalizes violations, while circulars promote green buildings[14]. In parallel, contractors are encouraged to adopt Environmental Management Systems (EMS) based on ISO 14001, as well as certifications such as LEED, LOTUS, or BREEAM. These improve competitiveness [15], reduces penalties and associated costs [16], ensure quality and safety[17,18], and enhance project value[19].

Numerous studies have examined the environmental impacts of construction activities. Numerous studies have focused on individual pollution types, such as dust and particulate matter [20–22], noise [23–26], water pollution, and liquid waste [27–29], or construction and demolition (C&D) waste [30–38]. However, most existing studies focus on single pollution types or specific activities, whereas integrated analyses that simultaneously cover air, noise, water, and solid waste pollution during the construction phase are still limited. Moreover, few studies have specifically examined pollution factors unique to high-rise buildings (HRBs). Unlike low-rise projects, HRBs present distinct technical challenges, such as deep excavations, massive concrete pours, and vertical material transport, which significantly intensify emission loads and prolong exposure durations [39,40]. Examining these specific factors is particularly critical within the context of Vietnam's urbanization, where the insertion of large-scale projects into high population density and narrow urban spaces exacerbates pollution dispersion and community health risks. Current literature often overlooks this specific interaction between high-rise typology and dense urban environments, failing to provide tailored mitigation strategies for such intensive construction sites. Finally, there is a lack of structured classification frameworks that systematically categorize pollution-contributing factors into meaningful groups, such as direct versus indirect factors, that can inform targeted mitigation strategies. Although Belayutham et al. introduced the concept of "proximal and distal factors" for water pollution [29], this framework has not been extended to encompass all types of pollution at construction sites.

Therefore, to fill this gap, this study develops a classification framework of factors specifically tailored to the high-rise context and proposes mitigation strategy priorities for these factors. The findings are expected to provide a foundation for further qualitative and quantitative analyses, as well as support preventive management strategies for project owners, contractors, consultants, and regulators.

2. Methodology

2.1 Research Approach and Search Strategy

This study employed a structured review approach, rather than a conventional Systematic Literature Review (SLR), to identify and classify environmental pollution factors at high-rise construction sites. Due to the nascent nature of research specifically focusing on pollution exclusively at high-rise sites. While an SLR typically requires a homogenous dataset for statistical aggregation, the current body of knowledge necessitates a more flexible, deductive approach. This method enables the inclusion of broader construction pollution literature, which is then critically analyzed in light of the specific technical characteristics of high-rise projects (e.g., deep excavation, vertical transportation, and high-density site constraints) to construct a comprehensive theoretical framework. This may serve as a baseline for future empirical validation in the Vietnamese context (e.g., expert interviews).

To ensure a comprehensive identification of pollution factors, the search strategy was structured to cover four specific types of pollution: Air, Water, Noise, and Solid Waste. The search was conducted on Web of Science, Scopus, ScienceDirect, and Google Scholar [41], covering the period 2010–2025. The search strings combined "specific type of pollution keywords" with "Construction context keywords" using Boolean operators (AND, OR). While the primary focus was on "high-rise construction sites", general terms like "Construction site" were also included to capture fundamental pollution factors (e.g., dust from concrete, noise from piling) that apply to vertical construction. The detailed search strings are presented in Table 1.

Table 1 *Search strings and keywords used in the review*

Type of pollution	Keywords and Search Strings
Air Pollution	("Air pollution" OR "Dust emission" OR "Particulate matter" OR "PM10/PM2.5") AND ("Construction site" OR "High-rise construction" OR "Building execution")
Noise Pollution	("Noise pollution" OR "Construction noise" OR "Sound emission") AND ("Construction site" OR "High-rise project" OR "Piling works" OR "Machinery operation")
Water Pollution	("Water pollution" OR "Wastewater discharge" OR "Runoff" OR "Sedimentation") AND ("Construction site" OR "High-rise building" OR "Excavation works")
Solid Waste	("Solid waste" OR "Construction and Demolition waste" OR "C&D waste") AND ("Construction site" OR "High-rise construction" OR "Material wastage")

2.2 Screening and Selection Process

Following the identification phase (resulting in 125 initial records), a multi-stage manual screening process was conducted to select the most relevant studies (Figure 1). First, titles and abstracts were screened to exclude duplicates and studies focusing on the operational phase or infrastructure (e.g., roads, bridges, tunnels). Only studies addressing the construction execution phase were retained (n = 60). Subsequently, due to the limited literature exclusively targeting high-rise pollution, this study reviewed general building construction literature and applied a qualitative filter based on high-rise technical features. Pollution factors were retained only if they were relevant to critical high-rise activities, specifically vertical material transportation, deep foundation works [40], and the amplification of dust dispersion due to wind loads at height [39]. Finally, the remaining studies underwent a quality appraisal. Articles were included only if they provided identifiable pollution factors supported by empirical data or clear qualitative observations. This resulted in 32 studies selected for the final synthesis.

2.3 Data Extraction, Classification, and Analysis

Pollution factors were systematically extracted from the selected 32 studies and organized using a Causal Classification Framework adapted from previous research on construction-site water pollution [28,29]. This classification serves a practical purpose, enabling stakeholders to distinguish between symptoms (Direct) that require immediate suppression and root causes (Indirect) that require upstream policy intervention.

- **Direct Factors (Proximal):** Defined as tangible on-site activities and physical processes that immediately release pollutants into the environment (e.g., earthworks, machinery operation, vertical material transportation).
- **Indirect Factors (Distal):** Defined as latent conditions, managerial decisions, or external environments that do not generate pollution directly but influence the occurrence and intensity of direct factors (e.g., design quality, project planning, workforce competence).

To resolve potential overlaps between categories, a "Root Cause Priority" coding rule was applied. Factors exhibiting a dual nature, such as rework, which generates physical waste (direct) but stems from design errors (indirect), were coded under their systemic origin (Indirect Factors). This approach ensures the analysis captures root causes, facilitating the identification of upstream preventive strategies rather than symptomatic controls.

To ensure the reliability of the categorization process, two authors independently coded the factors and subsequently cross-checked the results. Given that the study aimed for a qualitative classification rather than a quantitative scale measurement, Inter-Rater Reliability (IRR) metrics were not computed; instead, any discrepancies in categorization were resolved through discussion until a consensus was reached.

Finally, to quantify the significance of each factor within the reviewed literature, a frequency analysis was performed. The unit of analysis was the presence of a factor within a study (binary coding: 1 = presence, 0 = absence). The frequency (F) was calculated using the formula:

$$F(\%) = \frac{n}{N} \times 100 \quad (1)$$

Where:

- n is the number of studies citing the specific factor;
- N is the total number of included studies (N = 32). This quantitative step identifies the most critical pollution "hotspots" and consensus areas in current research.

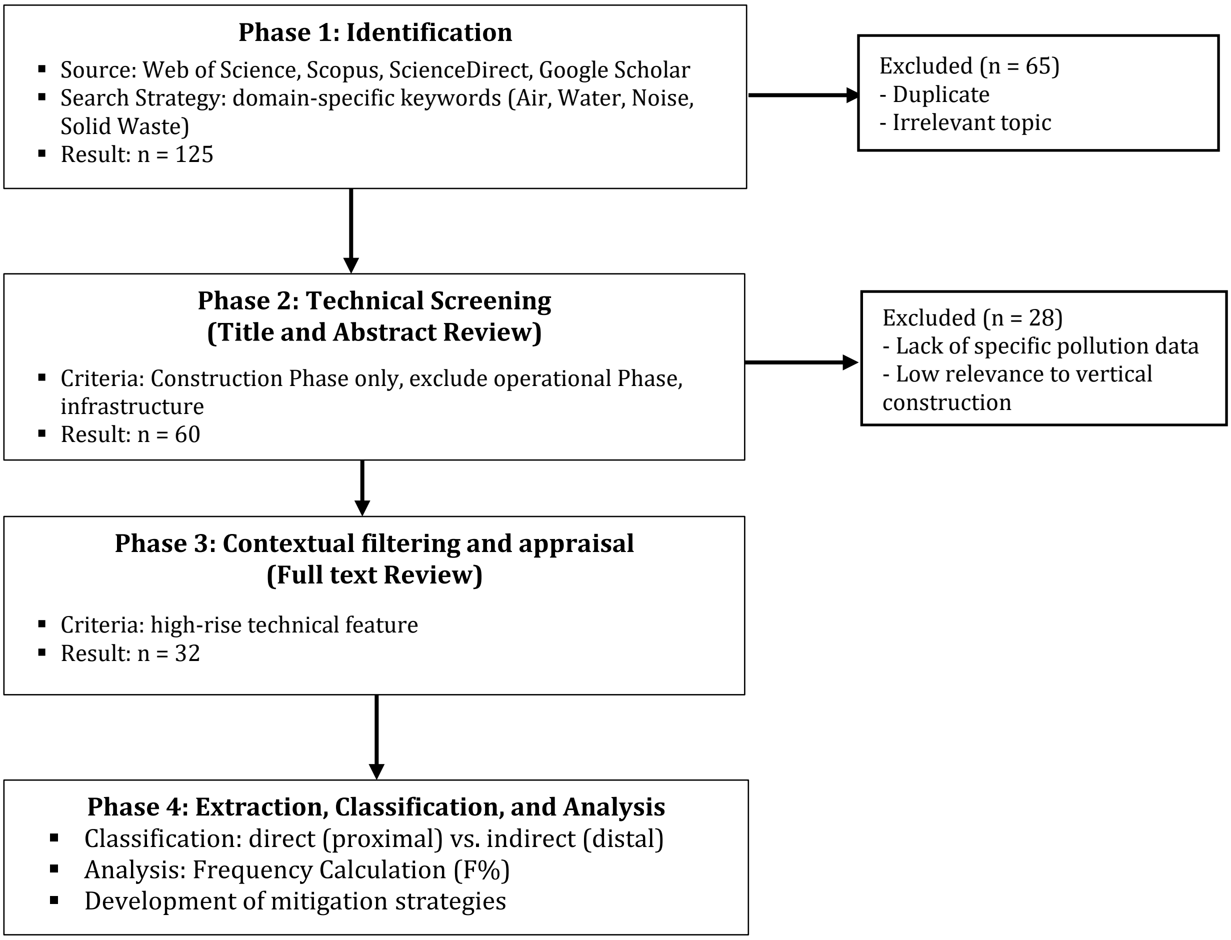

Fig. 1 *Research framework for the study*

3. Findings and Discussion

3.1 Categorization and Characteristics of Pollution Factors

Previous studies have extensively examined environmental pollution associated with construction activities and have proposed a wide range of mitigation strategies. The literature consistently highlights four principal categories of pollution generated during the construction phase: air, water, noise, and solid waste[20,21,42–45].

To address the complexity of high-rise construction without overwhelming detail, the extensive lists of specific activities have been consolidated into Table 2. This summary highlights the primary impact mechanisms for each pollution domain. The comprehensive inventory of activities and associated references is provided in Appendices A–D.

Table 2 *Summary of key environmental pollution factors at construction sites*

Type of Pollution	Factor Group	Key Sources and Impact Description
Air Pollution (See Appendix A)	I. Construction Process	Fugitive dust from site preparation, onsite construction activities, finishing works (cutting, grinding), and worker domestic activities
	II. Machinery and Equipment	Exhaust Emissions: CO, NO_x, SO_2, and PM released from internal combustion engines of heavy machinery (excavators, cranes).
	III. Transportation	Re-suspended Dust: Haulage trucks transporting materials/waste generate exhaust and re-suspend road dust on unpaved surfaces.
	IV. Indirect Factors	Macro-drivers: Socio-economic variables and financial constraints influencing the scale of emissions and technology adoption.
Noise Pollution (See Appendix B)	I. Direct Sources (Machinery and Equipment; Impacted-Related Activities; Manual Activities and Workforce)	Mechanical and Impulse Noise: Continuous noise from heavy machinery; high-intensity impulse noise from piling/breaking; and intermittent noise from power tools and workforce communication.
	II. Indirect Sources	Propagation: Site spatial characteristics (e.g., confined spaces, reflection from existing buildings) that amplify sound levels.
Water Pollution (See Appendix C)	I. Direct Sources	Wastewater and Runoff: Construction wastewater (washing, curing); Domestic sewage from workers; Stormwater runoff carrying sediments; Leaks and spills.
	II. Indirect Sources	Management and Nature: Managerial deficiencies (supervision, planning) and natural factors (heavy rainfall, topography) intensifying pollution risks.
Solid Waste (See Appendix D)	I. Direct Sources	Physical Generation: Waste arising directly from C&D activities (rework, demolition, surplus materials) and domestic waste from on-site workers.
	II. Indirect Sources	Root Causes: Design, Management, Material/Procurement; External.

3.1.1 Air pollution factors

Air pollution primarily stems from dust and gaseous emissions[21],[23]. Air pollution from construction activities is a complex, multi-source issue spanning nearly all project phases. These sources are interrelated, producing cumulative impacts on surrounding air quality. Among them, construction processes are the most diverse and persistent contributors, ranging from site preparation (including earthworks, demolition, and clearance) to finishing works. Finishing activities, such as the use of paints and solvents, release volatile organic compounds (VOCs)[46], while cutting, grinding, and drilling generate fine particulate matter (PM2.5 and PM10)[44,47–49]. Domestic subsistence activities of workers also contribute[21], indicating that pollution control requires a comprehensive rather than a narrow, activity-focused approach.

Construction machinery and equipment represent concentrated sources of toxic emissions. Diesel combustion produces particulate matter alongside exhaust gases (SO_2, NOx, CO)[20,22,44,47,50–52]. Emissions depend on engine type, fuel quality, and maintenance practices[20,44]. Heavy equipment and haul trucks also resuspend dust along access roads, especially on unpaved or poorly maintained surfaces[20,21,42–48,51,53]. At the broader scale, macro-level determinants such as GDP growth, urbanization rates, and financial constraints significantly influence both the scale and carbon intensity of the sector[53,54]. In practice, conflicts of interest often lead contractors to prioritize schedule and cost over environmental protection[53]. These findings imply that effective air pollution mitigation strategies require not only on-site measures (for example, dust suppression, equipment maintenance, cleaner fuels) but also urban planning, financial policies that encourage low-emission technologies and practices.

3.1.2 Noise Pollution Factors

Noise pollution is another critical environmental issue in construction, with severe implications for human health. Prolonged exposure to high noise levels has been linked to cardiovascular disease, sleep disorders, and increased mortality[55]. Noise pollution from construction activities can be grouped into two main categories: direct and indirect sources. Direct sources actively generate sound and constitute the dominant contributors. Among them, heavy machinery such as excavators, bulldozers, and pile drivers, along with transport vehicles, produces continuous noise from internal combustion engines[20,23–25,42–47]. Impact-related activities, including concrete breaking, pile driving, and blasting, create extremely high-intensity noise with immediate adverse environmental effects[20,26,42,44]. In addition, noise from manual activities and workforce behavior, such as the use of handheld power tools and loud vocal communication, also contributes significantly to overall site noise levels[24,25,44].

Indirect sources do not generate noise directly but intensify its propagation. Site and environmental conditions, particularly when construction occurs in confined spaces or near existing structures, amplify sound through reflection and reverberation[44].

Overall, construction noise pollution results from the interaction between direct sources and the physical environment. Effective mitigation strategies, therefore, require not only source-control measures but also site layout planning.

3.1.3 Water Pollution Factors

Water pollution from construction activities represents a significant environmental challenge, causing potentially irreversible damage to surrounding ecosystems and necessitating costly, resource-intensive remediation[42]. This pollution arises from multiple sources that affect both surface and groundwater quality.

Direct sources are point discharges, including process wastewater from equipment washing, concrete curing, material rinsing, and hydrostatic testing[20,21,27,42,43,45,47] as well as domestic sewage from the workforce[21,42,43,45]. These effluents typically contain high concentrations of suspended solids, oil, grease, and organic matter. In addition, stormwater runoff and erosion represent major non-point sources. Site preparation works, such as leveling and clearance, remove vegetative cover and make the soil highly vulnerable to erosion. Runoff then transports sediments and other pollutants (soil, grease, and chemicals) into receiving waters, degrading their quality[20,21,28,44]. Accidental spills and the intentional discharge of untreated wastewater can also trigger acute, localized toxic contamination[20,44].

Indirect sources do not generate pollutants themselves but intensify the risks associated with direct ones. Managerial and human-related deficiencies, such as poor planning, inadequate supervision, design errors, negligence, and construction delays, undermine pollution control effectiveness[28,29,44]. At the same time, natural conditions like heavy rainfall and challenging topography can greatly increase erosion and pollution severity[28,29].

Effective mitigation strategies for water pollution at high-rise construction sites require a combination of technical measures to address direct emissions and managerial actions to improve indirect factors such as stronger project management, better design practices, and greater stakeholder awareness.

3.1.4 Solid Waste Factors

Construction solid waste can be categorized into four groups: (a) recyclable; (b) reusable, either on-site or in other projects; (c) non-recyclable and non-reusable, designated for landfilling; and (d) hazardous waste [56]. In Vietnam, rapid urbanization and economic growth have driven widespread construction, renovation, and demolition activities, particularly in major cities such as Hanoi and Ho Chi Minh City. These operations generate substantial volumes of Construction and Demolition (C&D) waste, leading to resource wastage and substantial environmental impacts.

As with other pollution types, factors contributing to solid waste in construction are grouped into two categories: direct and indirect sources. Direct sources involve on-site activities and processes that physically generate waste. They are tangible points of waste production and often result from shortcomings influenced by indirect factors.

Construction and demolition (C&D) activities constitute a major share of waste. Rework caused by construction errors, repeatedly identified in prior studies[23,30,31,44], consumes additional materials and converts installed ones into debris such as concrete, bricks, and mortar. Demolition further produces large volumes of waste in the early stages[43,45]. In addition, surplus materials and packaging continuously contribute waste, including off-cuts, cement bags, plastic sheeting, scrap steel, and containers[20,21,44,45,47].

On-site domestic activities also generate waste, including organic (e.g., food scraps) and inorganic (e.g., bottles, bags, paper) components[21,42–45,47]. If unmanaged, these cause sanitation issues such as odors and pathogen growth.

Indirect sources are recognized as the root causes. Design-related deficiencies (frequent errors, changes, inaccurate drawings, and unclear specifications) are widely cited[23,30–35,44]. Meng et al. (2024) highlight that design decisions, such as increasing the rate of assembly and controlling the building height and floor area during the design, can reduce the generation of solid waste [35]. Early deficiencies often trigger chain reactions with long-term impacts.

Managerial problems exacerbate design flaws. Ineffective planning, weak supervision, and poor coordination create disorganized environments and delay problem resolution[23,30,31,33,34,36,37,44]. These weaknesses extend to the supply chain, including improper storage and handling[31,33,34,36,38], as well as procurement errors such as over-ordering[20,31,33,38,44].

Workers' behavior and attitudes play a decisive role: low skill levels, inexperience among technical staff, and poor workmanship cause significant errors[23,30,31,33,34,37,44]. Additionally, limited awareness and negative attitudes toward waste management increase waste volumes [31].

In summary, solid waste generation at construction sites is a systemic issue. Effective mitigation needs to address indirect sources rather than only treating the visible waste on-site.

3.2 Frequency Analysis and Classification

Based on the structured literature review, the identified environmental pollution factors were synthesized into a streamlined taxonomy comprising 27 key factors. These were categorized into Direct Sources (construction processes, machinery, human activities) and Indirect Sources (management, design, external factors). To quantify the significance of the identified factors, a frequency analysis was conducted based on the 32 selected studies. The results are presented in Table 3, categorized by the Direct/Indirect framework established in the Methodology. The frequency indicates the number of studies (n) and the percentage (%) of total studies (N = 32) that explicitly cited a specific factor as a contributor to each pollution type. The matrix highlights several important patterns.

Table 3 *Frequency matrix of pollutant factors across pollution type*

Group Factor		Detailed Factor	Frequency (%)			
			Air Pollution n (%)	Noise Pollution n (%)	Water Pollution n (%)	Solid Waste n (%)
I. Direct Factors Group						
Construction Process	1	Earthworks (excavation, land leveling, backfilling, site clearance)	10 (31.3)		6 (18.8)	
	2	Demolition and blasting of structures and non-conforming construction elements.	7 (21.9)	3 (9.4)		6 (18.8)
	3	Loading/Unloading, storage, and handling of construction materials	6 (18.8)			
	4	On-site material production and processing (e.g., cutting, crushing, grinding, drilling, concrete and mortar mixing)	7 (21.9)	1 (3.1)		
	5	Emissions and leaks/spills from materials (e.g., paints, solvents, chemicals, oil, and grease).	1 (3.1)		2 (6.3)	
	6	Impact-related noise activities (e.g., pile driving, erection/dismantling of scaffolding).		6 (18.8)		
	7	Construction Wastewater (washing vehicles/equipment, concrete curing, machinery cooling) and Runoff			7 (21.9)	
	8	Surface finishing, site cleaning, and waste removal	2 (6.3)			5 (15.6)

Machinery, Equipment, and Transportation	9	Operation of construction machinery and equipment (diesel engines)	7 (21.9)	10 (31.3)		
	10	Maintenance and servicing of machinery and equipment.	2 (6.3)			
	11	Material, soil, and waste haulage	11 (34.4)	5 (15.6)		
Human Activities on the Construction Site	12	Domestic activities of on-site workers.	1 (3.1)		4 (12.5)	6 (18.8)
	13	Loud vocal communication, shouting, and the use of loudspeakers on the construction site.		3 (9.4)		
II. Indirect Factors Group						
Management and People	14	Frequent design errors and changes, inaccurate drawings, and unclear material specifications.				8 (25.0)
	15	Poor supervision and control.			3 (9.4)	5 (15.6)
	16	Ineffective planning and scheduling				5 (15.6)
	17	Poor coordination and communication among stakeholders				4 (12.5)
	18	Poor skills of workers and technical staff, lack of experience, and selection of unqualified subcontractors.				7 (21.9)
	19	Poor attitude and work practices among parties (subcontractors, workers, site engineers).				6 (18.8)
	20	Lack of a formal waste management plan.				5 (15.6)
Material Management	21	Procurement errors (ordering incorrect materials) or ordering in excess of actual requirements.				5 (15.6)
	22	Improper on-site material storage and handling			2 (6.3)	5 (15.6)
Environmental and External Factors	23	Adverse weather conditions			2 (6.3)	3 (9.4)
	24	Site spatial characteristics: Construction near existing buildings or in environments with good echo and reverberation.		1 (3.1)		
	25	Project finance and budget issues	1 (3.1)			1 (3.1)
	26	Socio-economic factors (GDP, Population, Urbanization Rate)	1 (3.1)			
	27	Last-minute changes in customer demands or unforeseen incidents				2 (6.3)

First, the matrix identifies the primary pollution "hotspots" driven by direct operational activities. For air and noise pollution, the most frequently cited sources are material and waste haulage (Factor 11) and operation of construction machinery and equipment (Factor 9), with respective frequencies of 34.4% and 21.9% for air, and 15.6% and 31.3% for noise. This suits the logistical intensity of high-rise projects, where the vertical concentration of work necessitates continuous heavy-duty transport in confined urban spaces. Additionally, earthworks (Factor 1) emerge as a critical dual-pollutant source, recording high frequencies for air (31.3%) and noise (18.8%). This prominence is characteristic of high-rise construction, where deep excavation and extensive land leveling are prerequisites for structural stability. Regarding water pollution, Factor 7 (Construction Wastewater and Runoff) records the highest frequency (21.9%). This category consolidates various water-intensive activities, including

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washing vehicles/equipment, concrete curing, and machinery cooling. These processes were grouped because they share identical pollutant pathways, suspended solids, and chemical loads transported by direct discharge or stormwater-driven runoff. This finding highlights the critical challenge on high-rise sites, where limited space often forces these distinct waste streams to merge into a common drainage system, necessitating unified treatment solutions.

Second, solid waste generation, by contrast, is primarily associated with indirect, managerial causes rather than direct site operations. The most frequently cited are frequent design errors and changes, inaccurate drawings, unclear material specifications (Factor 14, 28.1%), poor worker and staff skills, lack of experience, and unqualified subcontractors (Factor 18, 21.9%), and negative attitudes and poor practices (Factor 19, 18.8%).

Third, the matrix illustrates the multi-impact nature of construction activities. For example, demolition and blasting of structures or defective elements (Factor 2) contribute to solid waste (18.8%), air (21.9%), and noise (9.4%). Domestic activities of workers (Factor 12) is a continuous multi-impact source, notably in solid waste (18.8%) and water pollution through wastewater discharge with high organic loads (12.5%). This interconnection suggests that isolated solutions are less effective than integrated management, where controlling one factor can simultaneously reduce several impacts.

Finally, the matrix reveals a notable absence of reported indirect factors (0%) specifically for Air and Noise pollution. It is crucial to interpret this finding with caution. This 0% does not imply that managerial or design decisions have no impact on these domains. This reveals a reporting bias rather than an absence of real-world causality. Previous studies have predominantly focused on quantifying physical emissions (e.g., PM concentrations, decibel levels) and direct sources, thereby overlooking upstream root causes. Mechanistically, however, indirect factors remain active drivers. For instance, design errors (indirect) necessitate rework, which extends machinery operation (direct) and intensifies emissions. Therefore, these zero values highlight a critical research gap: Air and Noise pollution are currently treated largely as technical problems, whereas they should be re-evaluated as systemic managerial challenges.

3.3 Propose Mitigation Strategies Based on Frequency Matrix Analysis

Analysis of the frequency matrix not only identifies key environmental pollution hotspots but also provides a scientific basis for targeted mitigation. Accordingly, three main strategic groups are proposed based on the highest-frequency factors:

1) Source control and immediate mitigation, focusing on mechanized construction processes and point-source discharges;
2) Upstream prevention, addressing design, construction planning, and material management practices;
3) Human resource management and stakeholder environmental awareness enhancement, emphasizing workforce management and supervision, and collaborative governance.

3.3.1 Source Control and Immediate Mitigation Strategy for Mechanized Construction and Point-Source Discharges

The matrix identifies Factor 1 (earthworks), Factor 9 (operation of machinery and equipment), and Factor 11 (material, soil, and waste haulage) as dominant contributors to air and noise pollution. These direct pollution factors require priority attention through immediate, at-source mitigation strategies.

A central measure is the modernization and proper maintenance of construction equipment. The adoption of new-generation machinery meeting stringent emission standards (e.g., Euro 4, Euro 5) and equipped with advanced noise abatement technology is essential. This approach, supported by Shaikh et al. and Yi Feng et al. [24,25], helps address GHG and toxic gas emissions noted by Yan et al. and Pakhomova et al. [51,52], while mitigating noise exposure for workers and nearby communities. Additional measures include optimizing site layouts to reduce particulate concentrations and noise propagation[57,58], and deploying real-time monitoring systems for pollution parameters[59].

Protective shielding and dust suppression are also required. These involve installing nets or tarpaulins around site perimeters and stockpiles, and operating automated misting systems, particularly in high dust-risk areas. Their effectiveness, however, depends on management awareness and commitment[48].

Finally, rational scheduling of construction hours is an important management solution. Restricting high-noise activities (e.g., pile driving, concrete breaking) during nighttime and midday breaks reduces community disturbance and reflects corporate social responsibility. This aligns with findings by J. Ayarkwa and K. Agyekum [60] and Lee et al.[26], which highlight variations in community noise annoyance across construction phases.

3.3.2 Upstream Prevention Strategy for Design, Planning, and Material Management

For solid waste, the frequency matrix indicates that root causes lie primarily in the pre-construction phase, particularly Factor 14 (frequent design errors and changes, inaccurate drawings, and unclear material specifications) and Factor 21 (procurement errors or over-ordering). Thus, upstream interventions are generally more effective and cost-efficient than downstream waste treatment.

The primary strategy is the early integration of environmental management into design. Key solutions include adopting prefabricated components to reduce on-site processing and cutting, thereby lowering waste, dust, and noise. A detailed, construction-feasible design minimizes errors and changes, which are primary causes of waste generation, as confirmed by Luangcharoenrat et al., Naji et al., and Chellappa et al.[31,33,34]. Additionally, switching to circular bio-based building materials is a viable strategy for sustainability. A comprehensive review by Le et al. [61]suggested that using these materials can represent a coherent solution to mitigate the climate impacts of the building sector according to the circular economy model.

Technology integration in the planning phase is also crucial. Building Information Modeling (BIM) supports precise material quantity take-offs, avoiding over-ordering and incorrect procurement [62]. It also enables early clash detection through 4D simulations, thereby preventing rework, a major source of waste and pollution. Numerous studies confirm that BIM is an effective tool in reducing waste from design errors and rework[63–65]. However, successful BIM implementation requires a solid legal basis. As noted by Dao et al. [66], establishing a contractual framework was proposed to minimize the risks in adopting BIM in Vietnamese construction projects, ensuring that environmental responsibilities are legally binding among stakeholders."

Finally, a comprehensive Waste Management Plan (WMP) should be established from the outset. The WMP must define procedures for on-site segregation, temporary storage, reuse, recycling, and final disposal for each type of waste. Such planning enables a shift from reactive to proactive waste management, as emphasized by Luangcharoenrat et al. and Liu et al.[33,38]. Furthermore, the application of Artificial Intelligence (AI) in waste management optimization also offers promising directions. Alimi et al. [67] emphasized that AI technology can improve operational efficiency, minimize environmental impacts, and enhance resource recovery in construction projects, addressing the limitations of manual waste treatment.

3.3.3 Human Resource Management and Stakeholder Environmental Awareness Enhancement Strategy

The frequency matrix highlights Factor 18 (poor skills of workers and technical staff, lack of experience, and unqualified subcontractors), Factor 19 (poor attitudes and practices among parties), and Factor 12 (domestic activities of on-site workers) as among the most frequently cited. Even well-designed technical solutions and management systems will not succeed without the active participation of people responsible for day-to-day implementation.

A core mitigation strategy is to strengthen environmental awareness and competencies through targeted training programmes. Training should be provided to all staff, from project managers and engineers to supervisors and labourers, and should focus on practical environmental management skills. Wu et al. and Kuluarachchi et al. demonstrated that awareness of consequences fosters responsibility and pro-environmental behaviors[53,68], while Bajjou et al. identified training and awareness raising as one of the five most critical factors in reducing material waste[37]. Topics may include segregation and handling, safe use and storage of chemicals, spill response, dust and noise control measures, and personal protective practices. Training content should clearly link environmental protection to occupational health, safety, and project efficiency to enhance motivation.

Strengthening on-site supervision is equally important. The role of supervision consultants should extend beyond technical and quality assurance to include strict monitoring of environmental compliance. Transparent protocols for reporting and addressing violations should be established and enforced, ensuring timely detection and corrective action.

From a managerial standpoint, embedding a corporate culture of environmental responsibility is essential. As Metinal and Ayalp note, contractor attitudes and capabilities are key determinants of waste generation[30]. Consequently, building such a culture, supported by incentive programs for material-saving behaviors (e.g., reducing operational errors, returning surplus materials)[69] and penalties for violations, can serve as a significant driver of behavioral change and long-term compliance with environmental regulations.

4. Conclusion

This study aimed to systematically identify and classify the primary factors contributing to environmental pollution at high-rise construction sites and to propose strategic directions for pollution mitigation in the Vietnamese context. A structured literature review of 32 key studies was conducted (2010-2025), focusing on pollution generated during the construction phase rather than the operational stage of buildings.

The analysis grouped pollution drivers into two broad categories: (1) Direct factors, including the construction process; machinery, equipment, and transportation; and on-site human activities; (2) Indirect factors cover management and people, material management, and external conditions. The frequency matrix shows that earthworks, machinery and equipment operation, material and waste haulage are the dominant sources of air and noise pollution. In contrast, solid waste generation is mainly driven by upstream managerial factors such as design errors and changes, inadequate planning and supervision, and poor workforce skills and attitudes. Several factors, notably demolition activities and workers' domestic activities, have multi-impact effects across different pollution types, underscoring the need for integrated rather than isolated control measures. A critical finding is the identification of a "reporting bias" in existing literature, where the link between managerial failures and air or noise emissions is often overlooked (recording a 0% frequency). This study argues that upstream errors, such as rework caused by design flaws, act as latent multipliers that intensify on-site machinery use and subsequent emissions, representing a significant "hidden link" in pollution mechanics.

Drawing on these findings, three complementary strategic directions are proposed: (i) source control and immediate mitigation for mechanized activities and point-source discharges; (ii) upstream prevention through enhanced design quality, planning, and material management; and (iii) strengthening human resources and stakeholder environmental awareness to improve on-site practices. These strategies provide a structured basis for contractors, consultants, and regulators to integrate environmental considerations into project management and to prioritize interventions according to pollution hotspots and root causes.

As this study is based on a literature review, the findings reflect the emphasis of prior research. Mitigation priorities are therefore derived from reported frequencies rather than empirical field data within the Vietnamese context. Future research should focus on quantifying and validating these factors using a mixed-methods approach. The first phase could involve semi-structured interviews with industry experts, followed by a questionnaire survey of stakeholders in high-rise construction to assess the practical significance of each factor in Vietnam. Such an approach will provide a robust scientific basis for comprehensive, feasible management solutions. Ultimately, it can support effective mitigation of environmental impacts from construction and contribute to the sustainable development of the sector in the context of Vietnam's rapid urbanization.

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Conflict of Interest

No potential conflict of interest was reported by the authors.

Declaration of Generative AI in Scientific Writing

During the preparation of this work, the authors used ChatGPT to assist the writing process more naturally. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Pham Thi Thanh Nhan, Nguyen Minh Ngoc;* ***data collection:*** *Pham Thi Thanh Nhan;* ***analysis and interpretation of results:*** *Pham Thi Thanh Nhan, Nguyen Anh Dung, Nguyen Minh Ngoc;* ***draft manuscript preparation:*** *Pham Thi Thanh Nhan, Nguyen Anh Dung. All authors reviewed the results and approved the final version of the manuscript.*

Appendix A *Detailed factors contributing to air pollution at construction sites*

Pollution Source	General Description	Specific Activities/Factors	Ref.
I. Sources from the Construction Process	Activities directly generating pollution during the main phases of a construction project, from commencement to completion.		
1. Site Preparation	Early-stage operations, such as land clearance, demolition, excavation, and leveling, release large amounts of dust (particulate matter) and exhaust emissions.	Earthworks (excavation, land leveling, backfilling, site clearance)	[20–22,42–44,46–48,53]
		Demolition and blasting	[20,43,44,46,48,49,53]
2. On-site Construction Activities	Core construction operations that generate significant dust and emissions.	Loading/unloading, storage, and handling of construction materials	[20,21,42,47,48,53]
		On-site material production and processing (cutting,	[20,44,46,48,49,53]

		crushing, concrete and mortar mixing)	
3. Finishing Works	Activities involving finishing materials (paints, solvents, asphalt) that emit volatile organic compounds (VOCs) and particulate matter.	Emissions from finishing materials (paints, solvents, asphalt)	[46]
		Cutting, grinding, and drilling	[44,47–49]
		Surface finishing, site cleaning, waste removal	[21,48]
4. Worker-Related Domestic Activities	Daily subsistence activities of on-site workers that generate combustion emissions and domestic waste.	Combustion of fuels (e.g., wood, LPG) for cooking and heating	[21]
II. Sources from Machinery and Equipment	Emissions from fuel combustion (gasoline, diesel) in construction machinery, releasing CO, SO_2, NOx, and particulate matter.	Operation of machinery and equipment (diesel engines)	[20,22,44,47, 50–52]
		Maintenance and servicing of equipment	[20,44]
III. Sources from Transportation	Pollution generated by vehicles transporting materials, soil, and waste to and from the site, including exhaust gases, fugitive dust, and re-suspended road dust.	Material, soil, and waste haulage	[20,21,42–48,51,53]
IV. Indirect Factors	Macro-level factors influencing the intensity and scale of emissions across the construction sector.	Socio-economic variables (GDP, population, urbanization rate)	[54]
	When conflict (time limitation, cost) occurs between the environment and economic benefit, the contractors often choose economic benefit rather than environmental protection.	Project finance and budget issues	[53]

Appendix B *Detailed factors contributing to noise pollution at construction sites*

Pollution Source	General Description	Specific Activities/Factors	Ref.
I. Direct Sources	Includes all activities that directly generate sound emissions into the environment during the construction process.		
1. Machinery and Equipment	Noise generated from the operation of heavy machinery and equipment, primarily from internal combustion engines.	Operation of heavy machinery and equipment: bulldozers, excavators, loaders, concrete mixers, etc.	[20,23–25,42–47]
		Operation of transport vehicles: material haulage, loading/ unloading	[20,24,25,42,43]
2. Impact-Related Activities	High-intensity, intermittent noise caused by forceful collisions between objects, such as piling, demolition, or blasting.	Foundation works: pile driving, press-in piling	[20,26,42,44]
		Demolition activities: dismantling of structures, use of concrete breakers;	[20,26,44]
		Other impact-related activities: dismantling of scaffolding and steel frames	[43,44]
3. Manual Activities and Workforce	Includes noise generated from handheld power tools and daily activities of on-site workers.	Manual construction activities: drilling, grinding, welding, hammering, knocking	[44]

		Worker activities: loud vocal communication, shouting, use of loudspeakers	[24,25,44]
II. Indirect Sources	Factors that do not directly create noise but amplify or modify its propagation characteristics.		
Site and Environmental Conditions	The presence of buildings, barriers, and other structures can cause sound reflection and reverberation, thereby increasing the overall noise impact.	Site spatial characteristics: Construction near existing buildings or in environments with good echo and reverberation.	[44]

Appendix C *Detailed factors contributing to water pollution at construction sites*

Pollution Source	General Description	Specific Activities/Factors	Ref.
I. Direct Sources	Includes all activities and processes that directly release pollutants into the aquatic environment or onto the land surface.		
1. Wastewater from Construction Activities	Wastewater is generated during construction operations, such as vehicle/equipment washing, concrete curing, and machinery cooling.	Washing vehicles/equipment; concrete curing; machinery cooling; hydrostatic testing; rinsing construction materials; concrete pouring and grouting	[20,21,27, 42,43,45,47]
2. Domestic Wastewater (Sewage)	Wastewater is generated from daily subsistence and sanitation activities of on-site workers.	Drinking, washing, bathing, and sanitation activities	[21,42,43, 45]
3. Stormwater Runoff, Erosion, and Sedimentation	A non-point source of pollution is caused when rainfall runs over exposed soil surfaces, transporting sediments and other contaminants.	Stormwater runoff carries soil, sand, oil, grease, chemicals, and debris	[20,21,28, 44]
		Site clearance, levelling, and excavation that cause topsoil erosion	[20,27–29,43,44]
4. Leaks, Spills, and Illegal Discharges	Pollution arising from accidental releases (oil/chemical leaks, spills) or intentional discharges (untreated wastewater).	Leakage or spills of oil, grease, paints, and solvents from storage or during construction	[20,43]
		Illegal dumping of construction materials or untreated wastewater into rivers, canals, or seas	[20,44]
II. Indirect Sources	Encompasses factors and conditions that do not directly generate pollutants but exacerbate the occurrence or severity of direct sources.		
1. Managerial, Human, and Design Factors	Deficiencies in planning, supervision, technical processes, or human behavior that undermine effective pollution control.	Poor supervision, contractor negligence, construction delays, inadequate control measures, design flaws, insufficient documentation, and budget constraints	[28,29,44]
2. Natural Factors	Pre-existing environmental conditions at the project site increase the risk and severity of pollution.	Adverse weather (e.g., heavy rainfall), topography, and geological characteristics of the site	[28,29]

Appendix D *Detailed factors contributing to solid waste generation at construction sites*

Pollution Source	General Description	Specific Activities/Factors	Ref.

I. Direct Sources	Activities and processes that directly generate solid waste at the construction site.		
1. Construction and Demolition (C&D) Activities	Waste arising directly from core construction and demolition operations.	Rework due to construction errors (demolition/replacement of non-conforming work)	[23,30,31,44]
		Demolition of existing structures or components	[43,45]
		Surplus materials after construction, packaging, and containers	[20,21,44,45,47]
2. Domestic (On-site) Activities	Waste generated from daily subsistence activities of the on-site workforce, similar in composition to municipal solid waste.	Household-type waste produced by workers' daily activities	[21,42–45,47]
II. Indirect Sources	Root-cause factors that do not directly create waste but establish conditions that increase waste generation from direct sources.		
1. Design Factors	Deficiencies in the design phase are a leading cause of rework and material wastage.	Frequent design errors and changes; inaccurate drawings; unclear material specifications	[23,30–35,44]
2. Management Factors	Weaknesses in project management lead to inefficient use of materials and resources.	Ineffective planning and scheduling	[23,31,33,34,36]
		Poor supervision and control	[23,31,33,34,37]
		Poor coordination and communication among stakeholders	[23,30,31,44]
		Lack of a formal waste management plan	[20,30,34,37,44]
3. Human Factors	Workforce competence and attitudes affect construction quality and the extent of material wastage.	Poor skills and limited experience among workers/technical staff, unqualified subcontractors	[23,30,31,33,34,37,44]
		Poor attitudes and practices among parties (subcontractors, workers, site engineers)	[30,31,33,34,38,44]
4. Material and Procurement Factors	Errors in the supply chain and on-site material management cause loss and damage.	Procurement errors (ordering incorrect materials) or over-ordering relative to requirements	[20,31,33,38,44]
		Improper on-site storage and handling of materials	[31,33,34,36,38]
5. External Factors	Objective conditions beyond the direct control of the project team that affect material-use planning.	Last-minute client changes or unforeseen incidents	[30,31]
		Adverse weather (e.g., heavy rain)	[23,31,36]
		Budget constraints are hindering waste minimization and recycling initiatives	[38]

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