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Exploring the factors contributing to environmental pollution 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, focus on the Vietnamese context. A systematic 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. 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 confirms the systemic nature of construction-related pollution and underscores the need for integrated strategies to ensure sustainable urban growth.

1. Introduction

The construction industry is a fundamental driver of Vietnam's economic development. According to the 2024 Socio-Economic Situation Report, the sector's GDP grew by 8.24 %, accounting for 45.17 % of the national GDP[1]. At the same time, rapid urbanization, fueled by rural-urban migration and the expansion of administrative boundaries, continues to accelerate. Currently, about 38.1 % of the population lives in urban areas, a proportion that has steadily increased over time[2]. This trend has intensified demand for housing and infrastructure, leading to a surge in high-rise building projects. For example, between 2010 and 2019, the number of apartments in Hanoi quadrupled, reaching 304,000 units, with approximately 35,000 flats added annually, double the average of 2010–2014[3].

However, this rapid growth has created substantial environmental risks. In Vietnam, 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]. Construction waste also accounts for 10–12 % of total urban solid waste[5]. Activities such as demolition, heavy machinery operation, material transport, concrete mixing, cutting, and grinding generate dust and emissions that seriously affect local air quality[5]. These impacts highlight the urgent need for pollution control measures.

Environmental pollution on construction sites is both multifaceted and interrelated. A single activity may simultaneously contribute to air, water, soil, and noise pollution. For instance, dust from excavation and transport not only degrades air quality and threatens the health of workers and nearby residents, but also settles on water surfaces and vegetation, thereby contaminating surface water and harming urban aesthetics. Prolonged exposure to adverse environmental conditions can also reduce labor productivity, increase healthcare costs and accident risks, and cause project delays[6]–[8]. Furthermore, community complaints or environmental incidents may lead to project suspension, resulting in financial and reputational losses for investors and contractors.

High-rise construction projects tend to intensify these impacts due to the concentration of materials, machinery, and labor in confined spaces. Deep foundation excavation and vertical material transport generate more dust, noise, waste, and emissions than low-rise projects. Indeed, a cluster of skyscrapers can produce greater lifecycle carbon emissions than an equivalent low-rise development[9]. These characteristics make mitigation strategies at high-rise construction sites particularly challenging and necessary.

Definitions of "high-rise" vary across countries. In the United States, it refers to buildings over 75 feet (23 meters) or seven stories[10], while in China it denotes residential buildings above 28 meters (10 stories) or commercial ones exceeding 24 meters[11].

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Vietnam's TCVN 9363:2012 defines high-rises as buildings between 9 and 40 stories[12]. These structures are characterized by large scale, complex techniques, significant material demand, and heavy machinery, all of which magnify their environmental impacts. Thus, adopting effective control measures for high-rise projects is both essential and urgent. Within the three pillars of sustainable development (environmental, economic, and social), the environmental aspect holds a position of primary importance for construction[13].

To address these concerns, Vietnam has developed a relatively comprehensive legal framework for environmental protection in construction activities. The 2020 Law on Environmental Protection, along with its guiding decrees and circulars, establishes principles for controlling air, water, and waste pollution, and mandates Environmental Impact Assessments (EIA) for investment projects. Decree 16/2022/ND-CP outlines penalties for violations, while Circular No. 02/2018/TT-BXD strengthens investor accountability for environmental protection. More recently, Decree 175/2024/ND-CP promotes green and energy-efficient buildings. The EIA process, reinforced by Decree No. 08/2022/ND-CP and Circular No. 02/2022/TT-BTNMT, serves as both a legal requirement and a technical management tool. By anticipating potential impacts before project approval, the EIA functions as a critical "filter," enabling the formulation of appropriate mitigation measures.

Beyond national legislation, contractors are increasingly encouraged to implement Environmental Management Systems (EMS) based on ISO 14001, especially in projects funded by foreign direct investment. The implementation of ISO 14001 helps contractors reduce waste, save costs, ease regulatory burdens, enhance public image, and improve worker health and safety[14].

Effective environmental management and mitigation strategies at high-rise construction sites, therefore, offer multiple benefits. For contractors and investors, it enhances corporate reputation, improves competitiveness[15], reduces penalties and associated costs[16], ensures quality control while safeguarding worker health and safety[17]. For local communities, mitigating dust, noise, and emissions helps maintain quality of life, reduces complaints, and fosters cooperation between residents and project stakeholders. For the government, better site-level practices contribute to national Sustainable Development Goals, as emphasized in the National Green Growth Strategy 2021–2030[18]. High environmental performance is also essential for achieving prestigious green building certifications, such as LEED (USA), LOTUS (Vietnam), and BREEAM (UK), which enhance the marketability and commercial value of projects[19].

In summary, addressing environmental pollution at high-rise construction sites is not only a legal or social obligation but also a driver of economic efficiency, sustainable development, and international integration. Against this backdrop, the present study aims to synthesise existing literature in order to: (i) identify the main environmental pollution factors at high-rise construction sites in Vietnam; (ii) classify these pollution factors into a structured framework; and (iii) propose mitigation strategies tailored to these factors. The findings are expected to provide a foundation for further qualitative and quantitative analyses and to support preventive management strategies for project owners, contractors, consultants, and regulators.

2. Methodology

This study employed a systematic literature review to identify and synthesise environmental pollution factors associated with high-rise construction sites and to derive appropriate mitigation strategies. The review focused on peer-reviewed journal articles, conference papers, and official reports that examine environmental pollution generated during the construction phase. Relevant publications were retrieved from four major databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar[20], using combinations of keywords related to construction, high-rise buildings, and environmental pollution.

The review targeted studies published within a defined time period that address pollution generated by construction activities rather than during the operational phase of buildings. A total of 125 studies published between 2010 and 2025 on the environmental impacts of construction activities were initially identified. The process of selecting and analyzing the relevant studies followed four main steps, as illustrated in Figure 1.

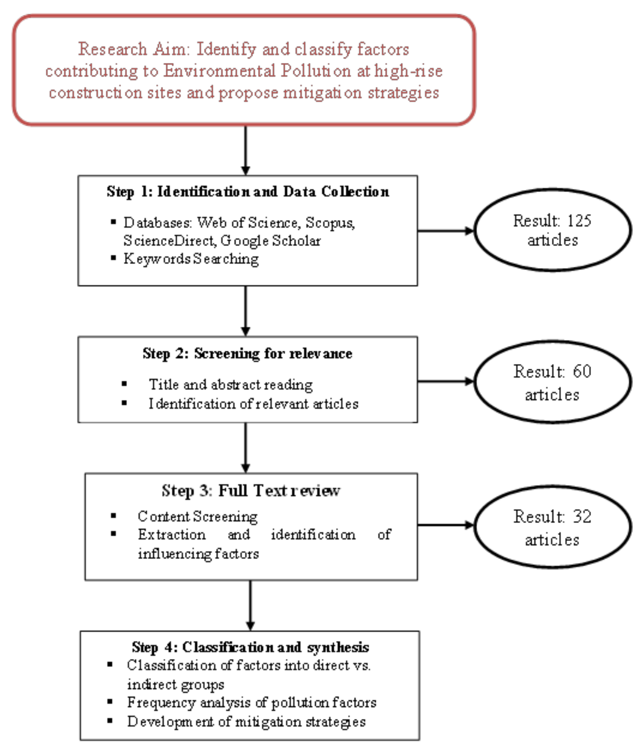

Fig. 1. Research framework for the study.

- **Step 1:** Identification and Data Collection. Research articles were retrieved from the selected databases using predefined keywords, resulting in 125 studies.

- Step 2: Screening for relevance to Research Objectives. Titles and abstracts were reviewed to determine relevance. Studies analyzing environmental pollution factors in construction were retained, while duplicate studies were excluded. This process resulted in 60 distinct studies.

- Step 3: Full-text review and extraction of pollution factors. The 60 studies were conducted, focusing on the significance and frequency of the identified factors. Ultimately, 32 highly relevant studies were selected for in-depth analysis.

- Step 4: Classification and Development of Mitigation Strategies. The identified factors were systematically categorized, and their frequency of occurrence across the reviewed literature was determined. In addition, strategies for mitigating pollution at construction sites were proposed.

3. Findings and Discussions

3.1. Summary of factors causing environmental pollution at construction sites from previous studies

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[21]–[26].

3.1.1. Air pollution factors

Air pollution primarily stems from dust and gaseous emissions[21],[23]. These originate from multiple sources of the construction process, as summarized in Table 1.

As shown in Table 1, 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)[31], while cutting, grinding, and drilling generate fine particulate matter (PM2.5 and PM10)[25], [27], [29], [32]. Domestic subsistence activities of workers also contribute[23], 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)[21], [25], [27], [28], [33]–[35]. Emissions depend on engine type, fuel quality, and maintenance practices[21], [25]. Heavy equipment and haul trucks also re-suspend dust along access roads, especially on unpaved or poorly maintained surfaces[21]–[27], [29]–[31], [34]. 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[30], [36]. In practice, conflicts of interest often lead contractors to prioritize schedule and cost over environmental protection[30]. 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[37]. The main sources of construction-related noise pollution, as identified in previous studies, are summarized in Table 2.

Table 2 shows that 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[21], [22], [24]–[27], [31], [38]–[40]. Impact-related activities, including concrete breaking, pile driving, and blasting, create extremely high-intensity noise with immediate adverse environmental effects[21], [22], [25], [41]. 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[25], [39], [40].

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[25].

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. Previous studies have documented these sources which are presented in Table 3.

As synthesized in Table 3, direct sources are point discharges, including process wastewater from equipment washing, concrete curing, material rinsing, and hydrostatic testing[21]–[24], [26], [27], [43] as well as domestic sewage from the workforce[22]–[24], [26].

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[21], [23], [25], [44]. Accidental spills and the intentional discharge of untreated wastewater can also trigger acute, localized toxic contamination[21], [25].

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[25], [42], [44]. At the same time, natural conditions like heavy rainfall and challenging topography can greatly increase erosion and pollution severity[42], [44].

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 [45]. 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. Table 4 presents the main factors contributing to solid waste generation throughout the project life cycle.

As with other pollution types, factors contributing to solid waste in construction are grouped into two categories: direct and indirect sources. As indicated in Table 4, 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[25], [38], [46], [47], 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[24], [26]. In addition, surplus materials and packaging continuously contribute waste, including off-cuts, cement bags, plastic sheeting, scrap steel, and containers[21], [23], [25]–[27].

On-site domestic activities also generate waste, including organic (e.g., food scraps) and inorganic (e.g., bottles, bags, paper) components[22]–[27]. 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[25], [38], [46]–[51]. 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 [51]. 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[25], [38], [46], [47], [49], [50], [52], [53]. These weaknesses extend to the supply chain, including improper storage and handling[47], [49], [50], [52], [54], as well as procurement errors such as over-ordering[21], [25], [47], [49], [54].

Workers' behaviour and attitudes play a decisive role: low skill levels, inexperience among technical staff, and poor workmanship cause significant errors[25], [38], [46], [47], [49], [50], [53]. Additionally, limited awareness and negative attitudes toward waste management increase waste volumes [47].

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. Classification and Discussion of Environmental Pollution Factors

To systematize the diverse environmental pollution factors identified in the literature, this study synthesized and classified them into a structured framework, distinguishing between direct and indirect pollution factors at high-rise construction sites. Direct factors denote on-site activities that generate pollution, whereas indirect factors represent latent, root-cause conditions whose impacts are often overlooked. This framework draws on causality theory, particularly research on water pollution at construction sites, which distinguishes between "proximal" (direct) and "distal" (indirect) factors[42].

Direct factors are closely associated with on-site operations and include: (1) the construction process; (2) machinery, equipment, and transportation, classified separately due to specific emissions from combustion engines; and (3) human activities on-site.

Indirect factors are classified into project management domains and external conditions. The groups "Design," "Planning and Supervision," and "Material Management" reflect issues spanning design, planning, supervision, and material control. "Environmental and External Factors" encompass objective conditions beyond the project's direct control but that exert significant influence, such as weather conditions or socio-economic factors.

Based on this classification, a frequency matrix was constructed from the 32 key studies to record how often each environmental pollution factor was linked to air, water, noise, and solid waste pollution. The matrix highlights several important patterns.

Table 1. 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)	[21]–[25], [27]–[31]
		Demolition and blasting	[21], [24], [25], [29]–[32]
2. On-site Construction Activities	Core construction operations that generate significant dust and emissions.	Loading/unloading, storage, and handling of construction materials	[21]–[23], [27], [29], [30]
		On-site material production and processing (cutting, crushing, concrete and mortar mixing)	[21], [25], [29]–[32]
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)	[31]
		Cutting, grinding, and drilling	[25], [27], [29], [32]
		Surface finishing, site cleaning, waste removal	[23], [29]
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	[23]
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)	[21], [25], [27], [28], [33]–[35]
		Maintenance and servicing of equipment	[21], [25]
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	[21]–[27], [29]–[31], [34]
IV. Indirect Factors	Macro-level factors influencing the intensity and scale of emissions across the construction sector.	Socio-economic variables (GDP, population, urbanization rate)	[36]
	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	[30]

Table 2. 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.	[21], [22], [24]–[27], [31], [38]–[40]
		Operation of transport vehicles: material haulage, loading/ unloading	[21], [22], [24], [39], [40]
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	[21], [22], [25], [41]
		Demolition activities: dismantling of structures, use of concrete breakers;	[21], [25], [41]
		Other impact-related activities: dismantling of scaffolding and steel frames	[24], [25]

Pollution Source	General Description	Specific Activities/Factors	Ref.
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	[25]
		Worker activities: loud vocal communication, shouting, use of loudspeakers	[25], [39], [40]
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.	[25]

Table 3. 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	[21]–[24], [26], [27], [43]
2. Domestic Wastewater (Sewage)	Wastewater is generated from daily subsistence and sanitation activities of on-site workers.	Drinking, washing, bathing, and sanitation activities	[22]–[24], [26]
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	[21], [23], [25], [44]
		Site clearance, leveling, and excavation that cause topsoil erosion	[21], [24], [25], [42]–[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	[21], [24]
		Illegal dumping of construction materials or untreated wastewater into rivers, canals, or seas	[21], [25]
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	[25], [42], [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	[42], [44]

Table 4. 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)	[25], [38], [46], [47]
		Demolition of existing structures or components	[24], [26]
		Surplus materials after construction, packaging, and containers	[21], [23], [25]–[27]
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	[22]–[27]
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	[25], [38], [46]–[51]
2. Management Factors	Weaknesses in project management lead to inefficient use of materials and resources.	Ineffective planning and scheduling	[38], [47], [49], [50], [52]
		Poor supervision and control	[38], [47], [49], [50], [53]
		Poor coordination and communication among stakeholders	[25], [38], [46], [47]
		Lack of a formal waste management plan	[21], [25], [46], [50], [53]
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	[25], [38], [46], [47], [49], [50], [53]
		Poor attitudes and practices among parties (subcontractors, workers, site engineers)	[25], [46], [47], [49], [50], [54]
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	[21], [25], [47], [49], [54]
		Improper on-site storage and handling of materials	[47], [49], [50], [52], [54]
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	[46], [47]
		Adverse weather (e.g., heavy rain)	[38], [47], [52]
		Budget constraints are hindering waste minimization and recycling initiatives	[54]

Table. 5. Detailed frequency matrix of pollutant factors in the Reviewed Literature.

Group Factor		Detailed Factor	Frequency (%)			
			Air Pollution	Noise Pollution	Water Pollution	Generated Solid Waste
I. Direct Factors Group						
Construction Process	1	Earthworks (excavation, land leveling, backfilling, site clearance)	31.3		18.8	
	2	Demolition and blasting of structures and non-conforming construction elements.	21.9	9.4		18.8
	3	Loading/Unloading, storage, and handling of construction materials	18.8			
	4	On-site material production and processing (e.g., cutting, crushing, grinding, drilling, concrete and mortar mixing)	21.9	3.1		
	5	Emissions and leaks/spills from materials (e.g., paints, solvents, chemicals, oil, and grease).	3.1		6.3	
	6	Impact-related noise activities (e.g., pile driving, erection/dismantling of scaffolding).		18.8		
	7	Washing vehicles/equipment, concrete curing, machinery cooling, combined with stormwater runoff carrying surface pollutants (soil, sand, oil and grease, and debris) into rivers, canals, or seas.			21.8	
	8	Surface finishing, site cleaning, and waste removal	6.3			15.6
Machinery, Equipment, and Transportation	9	Operation of construction machinery and equipment (diesel engines)	21.9	31.3		
	10	Maintenance and servicing of machinery and equipment.	6.3			
	11	Material, soil, and waste haulage	34.4	15.6		
Human Activities on the Construction Site	12	Domestic activities of on-site workers.	3.1		12.5	18.8
	13	Loud vocal communication, shouting, and the use of loudspeakers on the construction site.		9.4		
II. Indirect Factors Group						
Management and People	14	Frequent design errors and changes, inaccurate drawings, and unclear material specifications.				25.0
	15	Poor supervision and control.			9.4	15.6
	16	Ineffective planning and scheduling				15.6
	17	Poor coordination and communication among stakeholders				12.5
	18	Poor skills of workers and technical staff, lack of experience, and selection of unqualified subcontractors.				21.9
	19	Poor attitude and work practices among parties (subcontractors, workers, site engineers).				18.8
	20	Lack of a formal waste management plan.				15.6
Material Management	21	Procurement errors (ordering incorrect materials) or ordering in excess of actual requirements.				15.6
	22	Improper on-site material storage and handling			6.3	15.6
Environmental and External Factors	23	Adverse weather conditions			6.3	9.4
	24	Site spatial characteristics: Construction near existing buildings or in environments with good echo and reverberation.		3.1		
	25	Project finance and budget issues	3.1			3.1
	26	Socio-economic factors (GDP, Population, Urbanization Rate)	3.1			
	27	Last-minute changes in customer demands or unforeseen incidents				6.3

First, the matrix highlights the primary pollution "hotspots." For air and noise pollution, Factor 11 (material, soil, and waste haulage) and Factor 9 (operation of construction machinery and equipment) are the most frequently cited sources, with respective frequencies of 34.4 % and 21.9 % for air, and 15.6 % and 31.3 % for noise. In water pollution, Factor 7 (equipment washing and concrete curing, together with stormwater runoff carrying surface pollutants) records the highest frequency (21.8 %), indicating that on-site water use and concrete-related activities are the main contributors of effluent with immediate impact on aquatic environments.

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

Second, the matrix illustrates the multi-impact nature of several environmental pollution factors. For example, Factor 2 (demolition and blasting of structures or defective elements) contributes to solid waste (18.8 % , air (21.9 %), and noise (9.4 %). Factor 12 (domestic activities of workers) 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.

Third, differences in frequency across pollution types reflect uneven research attention. Studies on air, noise, and water pollution largely focus on tangible, direct sources, whereas research on solid waste often investigates systemic, indirect causes. This reflects a consensus that effective waste management requires interventions in early project stages (design, planning, and managerial capacity) rather than mitigation during construction, suggesting a growing recognition of the importance of project governance and institutional capacity for environmental pollution mitigation at high-rise construction sites.

Finally, the matrix suggests deeper causal relationships overlooked by current studies. For instance, factors in Group II (e.g., Management and People) show no direct association with air or noise, recording frequencies of 0 %. In practice, however, managerial deficiencies such as design errors (Factor 14) or poor technical skills (Factor 18) often lead to rework, extending machinery use and indirectly intensifying air and noise pollution. Addressing these root causes through improved design processes, integrated planning, and strengthened management may therefore be more effective than treating symptoms at the construction stage alone.

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. (2023) and Yi Feng et al. (2020)[39], [40], helps address GHG and toxic gas emissions noted by Yan et al. (2010) and Pakhomova et al. (2018)[34], [35], while mitigating noise exposure for workers and nearby communities. Additional measures include optimizing site layouts to reduce particulate concentrations and noise propagation[55], [56], and deploying real-time monitoring systems for pollution parameters[57].

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[29].

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 (2014)[58] and Lee et al. (2019)[41], 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. (2019), Naji et al. (2022), and Chellappa et al. (2023)[47], [49], [50].

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. 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[59]–[61].

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 waste type. Such planning enables a shift from reactive to proactive waste management, as emphasized by Luangcharoenrat et al. (2019) and Liu et al. (2020)[49], [54].

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. (2016) and Kuluarachchi et al. (2021) demonstrated that awareness of consequences fosters responsibility and pro-environmental behaviors[30], [62], while Bajjou et al. (2021) identified training and awareness raising as one of the five most critical factors in reducing material waste[53]. 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 (2024) note, contractor attitudes and capabilities are key determinants of waste generation[46]. Consequently, building such a culture, supported by incentive programs for material-saving behaviors (e.g., reducing operational errors, returning surplus materials)[63] and penalties for violations, can serve as a significant driver of behavioral change and long-term compliance with environmental regulations.

4. Conclusions

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 systematic literature review of 32 key studies was conducted, 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.

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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