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A STUDY ON EMISSION CHARACTERISTICS AND IMPACT ANALYSIS OF ODOR COMPOUNDS AND GASEOUS VOLATILE ORGANIC COMPOUNDS FROM LANDFILLS

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Abstract

Purpose: Global municipal solid waste (MSW) generation exceeds two billion metric tons annually and is projected to rise by 70% by 2050. Landfilling, the most common disposal method, releases volatile organic compounds (VOCs) and odorous substances that pose significant environmental and health risks. This study aims to synthesize current knowledge on the emission characteristics, influencing factors, and public health implications of VOCs and odorants emitted from landfills. **Research design, data and methodology:** A narrative review approach was applied, incorporating over 20 years of peer-reviewed literature and regulatory data. Databases such as PubMed, Scopus, and ScienceDirect were used to identify studies focused on emission sources, compound profiles, environmental factors, and health risk assessments. **Results:** The findings show that emissions are site-specific and influenced by waste composition, microbial activity, cover system integrity, and meteorological conditions. High-risk compounds including benzene, 1,3-butadiene, and trichloroethylene—pose carcinogenic risks, while hydrogen sulfide and ammonia affect quality of life through odor-related stress. Leachate storage pools and dumping areas were identified as emission hotspots. **Conclusions:** The study concludes that a comprehensive landfill emission management strategy should integrate real-time monitoring, health risk assessment, and AI-based prediction tools to better inform zoning, mitigation, and policy decisions for public health protection.

Keywords : Landfill emissions, VOCs, Odor compounds, Health risk assessment, AI-based monitoring

JEL Classification Code : K32, Q53, Q54, Q56,

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1. Introduction

Global waste generation has surged dramatically in recent decades, with annual production of municipal solid waste (MSW) exceeding two billion metric tons. Projections suggest a further 70% increase by 2050, driven by continued population growth, urbanization, and economic development (Statista, 2025). While recycling and energy recovery options are expanding, landfilling remains the most widely used waste disposal method across the globe. Compared to incineration and high-temperature composting, landfills offer advantages such as large capacity, operational simplicity, and low capital investment, making them especially common in developing regions (Schmidt et al., 2007). As a result, large-scale facilities like the Sudokwon Landfill in South Korea now handle upwards of 20,000 tons of waste daily, highlighting the scale and intensity of modern waste disposal practices (Statista, 2025).

Modern MSW consists of a complex mix of materials, including organic waste, plastics, metals, and a growing fraction of electronic waste (e-waste) now recognized as the fastest-growing waste stream globally. In 2022 alone, global e-waste generation reached 62 million metric tons, with a disproportionate burden in developing countries where disposal infrastructure remains inadequate (Statista, 2025). As waste decomposes within landfills, it undergoes intricate physical, chemical, and microbial processes that generate large volumes of gaseous by-products, many of which are harmful. These gases escape into the atmosphere through landfill covers, gas collection wells, or diffuse emissions, exposing both landfill workers and surrounding communities to a mix of odorous and toxic compounds (Slack et al., 2005).

The decomposition of organic matter estimated to constitute 50–70% of landfill waste under anaerobic conditions leads to the emission of a broad array of volatile organic compounds (VOCs) and odorous substances (Shao et al., 2021). These include aldehydes, ketones, aromatic hydrocarbons, alcohols, chlorinated compounds, and other semi-volatile pollutants (Gallego et al., 2014; Wang et al., 2021; Li et al., 2022). Among them, hydrogen sulfide is often detected at high concentrations both within landfill gas stacks and in surrounding ambient air, serving as a major contributor to odor complaints and community discomfort (Youn-Suk Son et al., 2007). Additional odorants such as propionic acid, styrene, and 2-pentanone, and VOCs such as toluene and m-xylene, have also been frequently identified. Notably, m-xylene has been proposed as a key indicator compound for assessing odor pollution due to its strong correlation with odor intensity and frequent detection in high-odor zones (Peng Lu et al., 2011).

Emission hot spots are often located in leachate storage pools, waste dumping areas, and sludge treatment zones, where the chemical composition of waste and microbial activity are most dynamic. Interestingly, some studies have observed that environmental factors such as temperature, humidity, and atmospheric pressure may have limited influence on VOC emission fluxes, suggesting that operational conditions, waste type, and landfill structure play a more dominant role (Gallego et al., 2014). Moreover, residential proximity, landfill geometry, and management quality especially at rural or understaffed facilities can exacerbate both exposure levels and health risks associated with landfill emissions (Zhang et al., 2021; Li et al., 2022).

Human exposure to these pollutants occurs mainly via inhalation, though dermal contact and indirect ingestion may also contribute, particularly in occupational settings. Inhalation is especially critical due to the volatile and dispersive nature of these compounds (Li et al., 2023b). Numerous studies have linked long-term exposure to compounds such as benzene, 1,3-butadiene, and trichloroethylene to carcinogenic outcomes, including leukemia, kidney damage, and neurological disorders (Fang et al., 2012; Wang et al., 2021). Even low-level exposure to odorants such as hydrogen sulfide can result in headaches, eye and respiratory irritation, and psychosocial stress, often leading to public health complaints in communities near landfill zones (Piccardo et al., 2022). These findings underscore the necessity for integrated assessments that consider both toxicological impacts and odor perception, particularly for vulnerable populations residing near active landfills.

Despite increased attention to landfill gas emissions in recent years, many studies remain site-specific and do not integrate chemical characterization, odor activity metrics, and health risk quantification into a unified framework. Moreover, most current assessments lack the use of advanced predictive tools such as AI-based models and large language models (LLMs) which could enhance our ability to analyze emission behavior, simulate dispersion, and estimate human exposure scenarios in near real-time.

1.1. Objectives of the Study

In response to these challenges and knowledge gaps, the aim of this study is to provide a comprehensive synthesis and critical analysis of VOC and odor emissions from landfills, with particular focus on their chemical profiles, influencing factors, and human health implications. Specifically, the objectives of this study are:

1. To identify and classify the major VOCs and odorous substances emitted from different landfill zones (e.g., dumping areas, leachate pools, and gas wells).

2. To examine the emission behavior and variability of these compounds, considering both environmental and operational factors.

3. To evaluate the potential health risks including both carcinogenic and non-carcinogenic effects using indicators such as hazard quotients, cancer risk indices, and odor activity values.

4. To explore the application of AI and large language models (LLMs) in emission prediction, health risk modeling, and decision-support for landfill management and environmental policy.

Through this integrated approach, the study seeks to contribute to the scientific understanding, regulatory improvement, and technological advancement of VOC and odor control in landfill operations, with the broader goal of enhancing public health protection and environmental sustainability.

2. Literature Review

Landfill emissions are a complex mixture of volatile organic compounds (VOCs) and odorous substances resulting from the anaerobic decomposition of organic matter and the volatilization of industrial and household chemicals. Numerous studies have focused on characterizing these emissions due to their significant contributions to environmental pollution, odor nuisance, and human health risks.

Fang et al. (2012) conducted a comprehensive study in China to identify odorous compounds emitted from various landfill zones. A total of 35 odorants were detected, including styrene, toluene, xylene, acetone, methanol, and n-butanone. The study also highlighted the prevalence of sulfur-containing compounds, particularly dimethyl sulfide, dimethyl disulfide, and hydrogen sulfide, which are known for their low odor thresholds and acute respiratory effects. In sludge-related areas, ammonia was found to dominate the odor profile, while volatile fatty acids, such as acetic acid and valeric acid, contributed significantly to the strong malodors observed in adjacent communities.

Expanding upon this, Li et al. (2023) investigated emission behavior and risk profiles in rural Chinese landfills. Their study detected between 45 and 68 VOC species and 27 to 37 odorous compounds, varying between the dumping areas and leachate storage pools. The VOCs primarily consisted of oxygenated compounds, chlorinated solvents, and aromatic hydrocarbons including benzene, trichloroethylene, and 1-chlorobutane. Measured VOC concentrations ranged from 82.63 to 806.34 mg/m³, while odorous compound levels reached up to 352.53 mg/m³. Importantly, the study linked elevated VOC emissions in warmer southern landfills with increased ozone formation potential and significant carcinogenic risks, particularly due to compounds like benzene and trichloroethylene.

Similarly, Wang et al. (2021) identified a total of 76 compounds, encompassing both VOCs and odorous gases, at a rural domestic landfill site in southwest China. Key VOCs included hexaldehyde, m-xylene, propylene oxide, acetophenone, and 2-butanone, whereas major odorants such as hydrogen sulfide, propionic acid, styrene, and 2-pentanone were detected at high concentrations. The study emphasized both the olfactory impact and the toxicological risks, identifying benzene, 1,3-butadiene, and trichloroethylene as the primary carcinogenic threats. These findings underline the need for targeted monitoring of high-risk compounds and site-specific emission control strategies.

Collectively, these studies demonstrate that landfill emissions vary significantly depending on waste composition, climatic conditions, and landfill infrastructure. While oxygenated VOCs often dominate in terms of concentration, it is the high odor activity value (OAV) compounds—such as hydrogen sulfide and methyl acrylate—that drive odor perception. Moreover, aromatic and chlorinated hydrocarbons frequently contribute to long-term health risks, necessitating their inclusion in routine risk assessments and regulatory frameworks.

Given the significant role of landfill VOCs and odors in contributing to air quality degradation, public health impacts, and community-level odor complaints, it is essential to continue refining our understanding of their chemical composition, spatial distribution, and dispersion behavior. This literature review therefore sets the foundation for the current study, which aims to consolidate knowledge on landfill-derived VOCs and odorants, assess the factors influencing their emission patterns, and explore their environmental and health implications using both conventional and AI-based analytical frameworks.

3. Research Methods and Materials

This narrative review was conducted to synthesize current scientific knowledge on the chemical composition, emission behavior, dispersion characteristics, and health impacts of volatile organic compounds (VOCs) and odorous substances emitted from landfill environments. A comprehensive literature search was performed using academic databases such as PubMed, Scopus, ScienceDirect, and Google Scholar, covering publications from the last two decades. To ensure a thorough and inclusive search, a wide range of keywords and Boolean search combinations were used. These included: *"landfill VOC emissions," "odor compounds from landfills," "health risks of landfill gases," "dispersion of landfill pollutants," "regulatory standards for landfill air pollution," "toxicological assessment of VOCs," "odor activity value landfill," "volatile organic compounds in waste management," "landfill gas exposure risk," "emission characteristics of MSW landfills," "environmental impact of landfill gases," "AI-based modeling of landfill emissions," "carcinogenic VOCs in landfill air," "non-*

methane volatile organic compounds (NMVOCs) from landfills," "odorous emissions and public health," "landfill gas dispersion modeling," "occupational exposure to landfill emissions," "landfill odor threshold compounds," and *"long-range transport of landfill pollutants."*

Studies were selected based on their relevance to key themes, including VOC and odorant composition, emission mechanisms, influencing factors such as microbial activity and landfill design, and associated health risks. Priority was given to articles that employed quantitative methods, identified high-risk compounds (e.g., benzene, trichloroethylene, hydrogen sulfide), used odor activity metrics or dispersion modeling, or assessed regulatory implications. Publications solely focused on non-airborne pollutants, groundwater contamination, or leachate chemistry were excluded to maintain the scope of airborne landfill emissions.

In addition to scientific articles, the review included regulatory and policy documents published by international and national agencies such as the United States Environmental Protection Agency (EPA), the European Environment Agency (EEA), and environmental authorities in China, South Korea, and European Union member states. These sources were reviewed to assess current emission thresholds, odor regulation frameworks, and best practices in landfill gas monitoring and mitigation.

Data was extracted from the selected sources and organized thematically, focusing on variables such as compound type, emission concentration, source zones (e.g., leachate pools, dumping areas), odor activity values (OAVs), dispersion patterns, and health risk indices (e.g., hazard quotient, cancer risk). The findings were then analyzed comparatively to identify trends, highlight gaps in the literature, and inform the framework for integrated landfill emission assessment. This methodological approach allowed for a comprehensive evaluation of landfill VOC and odor emissions within the context of environmental science, public health, and emerging AI-driven monitoring solutions.

Table 1: VOC and Odor Emissions and Their Specific Health Impacts

Compound	Type (VOC/Odor)	Common Sources	Emission Rate/Concentration (mg/m³)/μg/m³	Exposure Time	Health Effects	Cancer Risk Assessment (Inhalation Risk Level)	References
Ammonia (NH3)	Odor	Decomposing organic waste, livestock waste	0.1-5 (mg/m³)	Short to long term	Irritation of respiratory tract, exacerbation of asthma	Negligible	Piccardo et al. (2022), Wang et al. (2021)
Hydrogen Sulfide (H2S)	Odor	Anaerobic decomposition of sulfur compounds, landfills	0.0001-5(mg/m³)	Short term	Neurological symptoms, headaches, eye irritation	Negligible	Fang et al. (2012), Wang et al. (2021)
Methanethiol (CH4S)	Odor	Decay of proteins in waste, wastewater treatment	0.001-1(mg/m³)	Short term	Eye irritation, nausea, respiratory discomfort	Negligible	Fang et al. (2012), Pan et al. (2023)
Dimethyl Sulfide (C2H6S)	Odor	Microbial breakdown of organic matter, landfills	0.001-1(mg/m³)	Short term	Unpleasant smell, headaches, nausea	Negligible	Pan et al. (2023), Li et al. (2023a)
Dimethyl Disulfide (C2H6S2)	Odor	Anaerobic digestion of waste, industrial waste	0.001-1(mg/m³)	Short term	Respiratory distress, nausea, discomfort	Negligible	Li et al. (2023a), Wang et al. (2021)
Toluene (C7H8)	VOC	Industrial waste, adhesives, solvents, landfill gas	0.01-5(mg/m³)	Long term	Neurotoxicity, liver and kidney damage, developmental toxicity	Possible Risk	Du et al. (2014), Wang et al. (2021), Fan et al. (2025)
Benzene (C6H6)	VOC	Vehicle emissions, industrial processes, landfills	0.001-1(mg/m³)	Long term	Carcinogenic (leukemia), central nervous system damage,	Definite Risk	Du et al. (2014), Wang et al. (2021), Li et al. (2023a), Fan et al. (2025)

					bone marrow toxicity		
Xylene (C_8H_{10})	VOC	Paints, solvents, coatings, landfill gas	0.001-2(mg/m³)	Long term	Respiratory irritation, dizziness, headaches	Possible Risk	Du et al. (2014), Wang et al. (2021)
Ethanol (C_2H_6O)	VOC	Fermentation, waste processing, bioethanol production	0.1-10(mg/m³)	Short term	Mild irritation, dizziness, potential liver effects	Negligible	Pan et al. (2023), Wang et al. (2021)
Acetone (C_3H_6O)	VOC	Solvent use, industrial emissions, landfill gas	0.1-10(mg/m³)	Short term	Headaches, dizziness, irritation, neurotoxicity	Negligible	Li et al. (2023a), Wang et al. (2021)
Styrene (C_8H_8)	VOC	Plastics manufacturing, combustion emissions	0.5-5(mg/m³)	Long term	Irritation of eyes and mucous membranes, potential carcinogen	Probable Risk	Wang et al. (2021), Piccardo et al. (2022)
1,3-Butadiene (C_4H_6)	VOC	Petroleum refining, rubber production	0.3-2(mg/m³)	Long term	Carcinogenic, central nervous system effects	Definite Risk	Wang et al. (2021), Li et al. (2023)
Trichloroethylene (C_2HCl_3)	VOC	Industrial degreasing, dry cleaning	0.2-1.5(mg/m³)	Long term	Carcinogenic (kidney and liver cancer), neurotoxicity	Definite Risk	Wang et al. (2021), Fang et al. (2012)
Ethylbenzene	VOC	Landfill working surface, industrial processes	0.032–0.142 µg/m³	Short to long-term	Affects central nervous system, potential carcinogen (liver, blood)	Minor to Moderate Risk (0.1–0.2%)	Li et al. (2023b)
Benzene	VOC	Landfill working surface, vehicle emissions, industrial processes	0.003–0.011 µg/m³	Short to long-term	Carcinogenic (leukemia), CNS and bone marrow toxicity	Minor Risk (0.1–0.2%)	Li et al. (2023b)
Chloroform	VOC	Landfill waste degradation, chemical residues	0.007–0.027 µg/m³	Short to long-term	Liver and kidney toxicity, central nervous system effects	Moderate Risk (0.1–1%)	Li et al. (2023b)
1,2-Dichloroethane	VOC	Chlorinated solvents in waste, landfill gas	0.006–0.056 µg/m³	Short to long term	Respiratory irritation, liver damage, potential carcinogen	Moderate Risk (0.1–0.7%)	Li et al. (2023b)
1,2-Dichloropropane	VOC	Chemical residues, industrial waste	0.020–0.120 µg/m³	Short to long term	Central nervous system effects, gastrointestinal disturbance	Negligible	Li et al. (2023b)
Tetrachloroethylene	VOC	Dry cleaning, industrial degreasers, landfill gas	0.002–0.017 µg/m³	Short to long term	Neurotoxicity, kidney and liver carcinogen	Negligible to Low Risk	Li et al. (2023b)

4. Results and Discussion

4.1. Emission Characteristics of Odor Compounds and VOCs

The emission of volatile organic compounds (VOCs) and odorous substances from landfills represents a complex interaction of biochemical degradation, physicochemical transformation, and environmental dispersion processes. These emissions not only contribute to ambient air pollution but also pose significant nuisance and public health risks, especially in densely populated or poorly managed landfill-adjacent regions. VOCs and odorants are released during the anaerobic degradation of organic waste, microbial fermentation, and volatilization of industrial and household chemical residues embedded in municipal solid waste (Lee et al., 2016; Yoon & Kim, 2012; Li et al., 2023a; Pan et al., 2023).

From the perspective of emission behavior, landfill gas is characterized by a diverse chemical composition, primarily consisting of sulfur-containing compounds (e.g., hydrogen sulfide, dimethyl sulfide, dimethyl disulfide), nitrogenous substances (e.g., ammonia), and aromatic and halogenated VOCs such as benzene, toluene, xylene, and trichloroethylene. These compounds are generated from both natural organic matter, such as food and vegetation waste, and synthetic waste components, including plastics, solvents, and disinfectants. The emission dynamics are governed not only by compound concentration but also by their odor thresholds and odor activity values (OAVs), with certain compounds exerting significant olfactory influence even at trace concentrations.

In alignment with the goals of this study, understanding these emission characteristics is crucial for developing targeted mitigation strategies that address both the toxicological burden and odor perception impacts associated with landfill gases. The linkage between waste composition, environmental conditions, and emission profiles forms the scientific basis for assessing health risks, regulatory compliance, and odor control interventions.

4.2. Composition and Sources of Odorous and VOC Emissions from Landfills

Odorous and VOC emissions in landfill environments originate primarily from two key pathways: (1) microbial decomposition of organic material under anaerobic conditions, and (2) volatilization of anthropogenic chemicals from waste residues and leachate. This dual origin results in a chemically heterogeneous mixture composed of sulfur compounds (e.g., hydrogen sulfide, methyl mercaptan, dimethyl disulfide), nitrogenous gases (e.g., ammonia), oxygenated compounds (e.g., aldehydes, ketones, organic acids), aromatics (e.g., benzene, toluene, styrene), and chlorinated solvents (e.g., trichloroethylene, dichloromethane) (Pan et al., 2023; Wang et al., 2021; Liu et al., 2020).

A study conducted by Li et al. (2023a) on rural domestic waste landfills in China revealed that 45–68 VOCs and 27–37 odorants were consistently emitted across different landfill functional zones. The dumping area (LDA), where active degradation occurs, emitted a broader spectrum of VOCs, dominated by ethyl acetate, propylene oxide, and limonene. In contrast, the leachate storage pool (LSP) exhibited higher levels of chlorinated compounds and sulfur-rich gases, such as dimethyl sulfide and trichloroethylene, reflecting chemical leaching and accumulation processes.

Oxygenated compounds were the most abundant chemical class across all zones, comprising over 48% of the total VOC mass. However, odor perception was predominantly influenced by high-OAV compounds like hydrogen sulfide and methyl acrylate, which, despite lower concentrations, exerted disproportionate olfactory effects (Lee et al., 2016; Yoon & Kim, 2012). This distinction is essential for prioritizing odor control efforts based on sensory impact rather than mass concentration alone.

Spatially, the southern landfill (SLF), characterized by higher ambient temperatures and humidity, exhibited significantly greater VOC concentrations (up to 806.34 mg/m³) than the northern landfill (NLF) (ranging from 82.63 to 124.86 mg/m³) (Li et al., 2023a). This finding reinforces the role of meteorological and climatic factors in amplifying emission intensity and chemical diversity. Elevated temperature accelerates microbial activity and volatilization rates, increasing emission fluxes of both VOCs and odorants. These insights have direct implications for climate-sensitive landfill management practices.

Supporting this, Fang et al. (2012) identified 35 odorous compounds across various landfill operational areas, grouped into six chemical categories: ammonia, sulfur compounds, aromatic hydrocarbons, oxygenated compounds, amines, and volatile fatty acids (VFAs). Municipal waste zones emitted high levels of styrene, acetaldehyde, and n-butylaldehyde, while sludge treatment areas were dominated by ammonia, acetic acid, dimethyl disulfide (DMDS), and methyl mercaptan (MM). Interestingly, while compounds like ammonia and aromatics were most abundant, low-threshold substances such as DMDS, DMTS, and acetic acid had the greatest impact on odor perception. The study proposed DMDS and MM as effective marker compounds for odor monitoring due to their strong olfactory influence and toxicological significance.

These findings collectively indicate that emission patterns are site-specific, shaped by waste characteristics, age, microbial succession, and landfill design. Both the LDA and LSP emerge as priority zones for emission monitoring and control due to their elevated pollutant loads and direct exposure pathways. For the purposes of this study, this reinforces the need to evaluate not only the chemical concentration profiles but also the odor and health risk implications of dominant VOCs and odorants. A nuanced understanding of source composition and behavior is essential for establishing evidence-based mitigation strategies, especially in communities where landfill emissions intersect with public health vulnerabilities. (See figure 1)

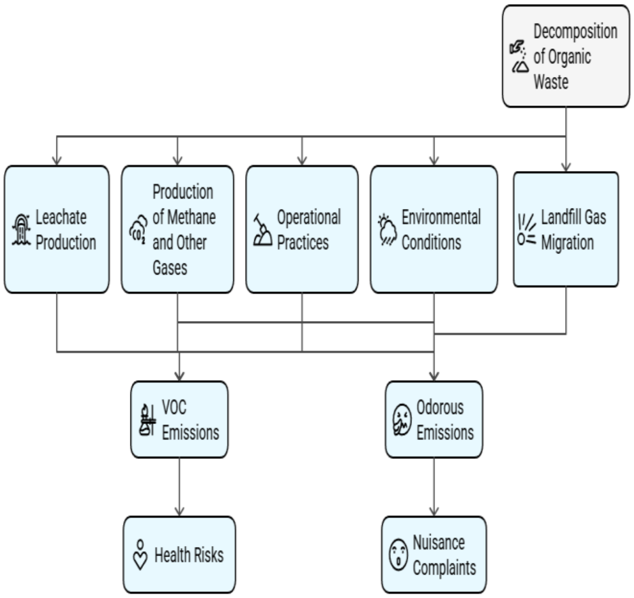

Figure 1: Conceptual pathway of VOC and odorous emissions from landfills, illustrating how organic waste decomposition and site-specific conditions contribute to environmental and health impacts.

4.3. Key Determinants Influencing Emissions of VOCs and Odorous Compounds from Landfills

The emission rates, chemical composition, and atmospheric behavior of volatile organic compounds (VOCs) and odorous substances from landfill sites are governed by a set of complex and interrelated. These include waste characteristics, microbial degradation dynamics, landfill engineering and operational practices, environmental parameters, and meteorological conditions factors as shown in Figure 2. Understanding how these determinants influence the generation, transformation, and dispersion of gaseous pollutants is essential for developing effective mitigation strategies, assessing human health risks, and enhancing the regulatory management of landfill air emissions. A long-term study conducted by Chiriac et al. (2009) at a French municipal solid waste (MSW) landfill highlighted the spatial and temporal variability of VOC emissions. Using passive Radiello samplers at twelve three-dimensionally distributed monitoring points over one year, the researchers tracked the dispersion patterns of sixteen VOCs, including benzene, toluene, trichloroethylene, tetrachloroethylene, and limonene. The results confirmed that the active landfill cell was the primary source of VOCs. Emission concentrations generally decreased with distance from the source but were significantly influenced by the site's morphological features, meteorological variables, and physical barriers such as vegetation and topography. Notably, VOC concentrations during dry periods were found to be up to 2.65 times higher than during wet conditions, indicating the strong influence of moisture content and temperature on volatilization rates. While highly reactive compounds such as limonene showed steep declines with distance, persistent pollutants like benzene were still detectable at remote sites—suggesting diffuse leaks from older landfill cells or biogas infrastructure. Additionally, environmental features such as hills and shrubs occasionally redirected VOC plumes, creating unexpectedly high concentrations at further distances, thereby complicating conventional dispersion predictions. The study emphasized that wind direction, temperature gradients, and landfill operational parameters, including daily waste volume and compaction density, all played significant roles in modulating both the dispersion and intensity of emissions.

4.3.1. Waste Composition and Moisture

The chemical composition and physical properties of waste particularly the proportion of biodegradable material and moisture content—are primary drivers of VOC and odorant generation. Landfills rich in organic waste such as food residues, paper, yard trimmings, and textiles exhibit significantly higher emission levels due to microbial anaerobic degradation. Specific waste types influence the types of gases produced; for example, protein-rich materials like meat and dairy lead to elevated emissions of sulfur-containing compounds, including hydrogen sulfide and mercaptans, while fermented organic matter releases high concentrations of ketones, aldehydes, and organic acids (Shao, 2010; Pan et al., 2023). Moisture content further enhances microbial activity, promoting fermentation and methanogenesis, and thereby increasing the release of odorous intermediates (Li et al., 2023a). Consequently, both the quantity and quality of waste are foundational determinants of emission magnitude and chemical diversity. (See figure 2)

4.3.2. Microbial Activity and Degradation Stage

The microbial community composition and degradation stage of the waste mass critically influence the temporal variation in emission profiles. During the initial degradation phase, labile substrates support rapid microbial activity, resulting in the emission of compounds such as methyl acrylate, acetaldehyde, ketones, and thioethers. As the waste matures and microbial succession occurs, these compounds tend to diminish, giving way to more stable gases like methane and carbon dioxide (Shao, 2010). Thus, the age of the landfill cell, coupled with the metabolic stage of microbial processes, determines the chemical composition and intensity of emissions over time. (See figure 2)

4.3.3. Landfill Design and Cover System Integrity

The engineering design and maintenance of landfill infrastructure significantly affect the magnitude and pathways of gas release. Key elements such as the geomembrane integrity, leachate recirculation systems, and landfill gas collection networks play critical roles in either containing or allowing the escape of pollutants. Compromised cover systems, especially over the dumping area (LDA), serve as primary sources of fugitive emissions. A study by Wang et al. (2019) observed that limonene concentrations were markedly higher in regions where cover materials had degraded, underscoring the importance of regular structural inspection and repair. Effective leachate drainage and gas venting systems are essential to minimize overpressure, which can force emissions through cracks and leaks in landfill caps. (See figure 2)

4.3.4. Environmental and Climatic Conditions

Ambient environmental conditions such as temperature, humidity, and barometric pressure exert significant influence on both microbial activity and the volatility of chemical compounds. Elevated temperatures accelerate biodegradation rates and enhance the diffusion coefficients of VOCs, leading to higher emission fluxes. Comparative analysis of two rural landfills in China SLF (Southern Landfill Facility) and NLF (Northern Landfill Facility) demonstrated that the SLF, which experiences higher temperatures (29.8°C) and relative humidity (67.1%), exhibited more complex chemical profiles and significantly greater VOC concentrations than the cooler NLF site (Li et al., 2023a). Seasonal changes also contribute to emission variability. During warmer months, sulfur-based emissions such as hydrogen sulfide increase due to enhanced microbial sulfur metabolism, whereas terpenes like limonene become more prevalent in cooler periods (Wang et al., 2021). In addition, the physicochemical properties of each compound—such as molecular weight, vapor pressure, and atmospheric half-life—determine their dispersion potential. For example, benzene and trichloroethylene have longer atmospheric lifetimes and can travel distances exceeding 1,000 meters, whereas heavier sulfur compounds tend to remain near their emission sources due to rapid reactivity and lower volatility (Chiriac et al., 2009). (See figure 2)

4.3.5. Meteorological Factors and Atmospheric Transport

Meteorological variables, particularly wind speed, wind direction, atmospheric turbulence, and thermal inversion layers, directly control the transport, dilution, and ground-level concentrations of emitted compounds. Dispersion modeling using the HYSPLIT system at SLF and NLF revealed significant contrasts in atmospheric behavior. The SLF, characterized by low wind speeds (1.39 m/s), exhibited localized accumulation of VOCs and odorants, whereas the NLF, with higher wind speeds (2.58 m/s), facilitated broader dispersion, potentially increasing the geographic extent of human exposure (Li et al., 2023a). Similar findings have been reported near pneumatic waste collection and processing facilities, where hydrogen sulfide, ammonia, and various VOCs from storage and transport operations were transported to nearby residential zones, degrading air quality and prompting health complaints (Wang et al., 2021).A high-resolution simulation-based study conducted at a municipal landfill in Beijing, China, identified six high-risk VOCs—ethylbenzene, benzene, chloroform, 1,2-dichloroethane, 1,2-dichloropropane, and tetrachloroethylene as major airborne pollutants emitted from the active working surface. Using 8,753 Monte Carlo-enhanced ModOdor simulations over a one-year period, the study demonstrated that maximum concentrations occurred within 100–600 meters of the source, influenced strongly by prevailing wind patterns (Li et al., 2023b). At a 95% cumulative probability, concentrations at 100 meters from the landfill ranged from 0.003 μg/m³ (benzene) to 0.142 μg/m³ (ethylbenzene). These concentrations decreased by over 75% at distances of 1,000 meters. Dispersion distances varied from 200 to 2,500 meters, depending on compound reactivity, volatility, and degradation potential. These findings highlight the importance of integrating site-specific meteorology and compound-specific behavior into emission risk modeling frameworks. (see figure 2)

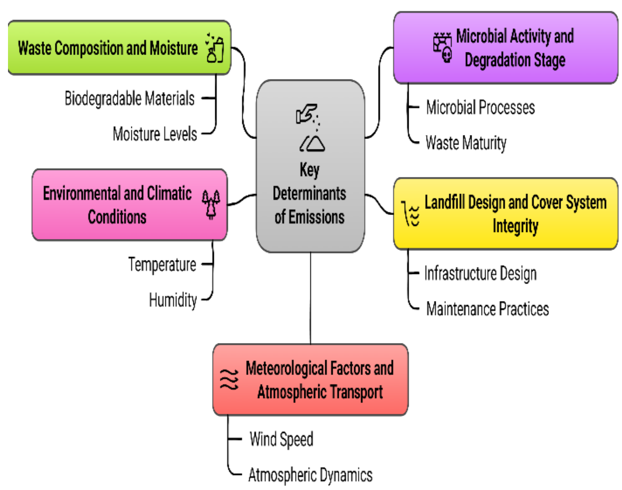

Figure 2: Key Environmental and Operational Factors Influencing VOC and Odorous Emissions from Landfills

4.5. Toxicity and Environmental Impact of VOCs and Odor Compounds

The emission of volatile organic compounds (VOCs) and odorous substances from landfills represents a significant environmental and public health concern due to the toxic, carcinogenic, and atmospheric-reactive properties of these compounds (see Figure 3). Many VOCs, particularly aromatic hydrocarbons, chlorinated solvents, and oxygenated organics, are known to contribute to acute toxicity, chronic diseases, and atmospheric degradation processes. Their environmental impact is magnified by the complex interactions they undergo once released into the air, including photochemical reactions, secondary pollutant formation, and long-range atmospheric transport.

Among the most hazardous VOCs emitted from landfills are the BTX compounds—benzene, toluene, and xylene. Benzene, in particular, has been classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) and has been linked to hematopoietic malignancies, such as leukemia, through prolonged inhalation exposure (Wang et al., 2021). Toluene and xylene, though less carcinogenic, are known to cause neurological disorders, respiratory irritation, and reproductive and developmental toxicity, especially at elevated concentrations or during chronic exposure periods. These compounds are frequently found in landfill gas emissions, particularly in zones such as the leachate storage pool (LSP) and dumping area (LDA), where microbial degradation and chemical leaching are most active (Wang et al., 2021).

Chlorinated VOCs, such as trichloroethylene, chloroform, and 1,3-butadiene, also contribute to significant toxicological and environmental risks. Trichloroethylene and 1,3-butadiene are well-established carcinogens, with links to liver, kidney, and blood cancers. These compounds also possess high vapor pressures and low odor thresholds, making them both respiratory hazards and contributors to odor pollution even at low concentrations (Li et al., 2023a; Fang et al., 2012). The dominant emission zones for these substances have been identified as LSPs and uncovered waste surfaces, which often lack adequate gas capture infrastructure. This spatial localization underscores the need for targeted emission control at the most active and exposed landfill zones.

Beyond their direct health implications, many VOCs and odorous compounds released from landfills exert environmental impacts through secondary pollutant formation. Oxygenated compounds and chlorinated VOCs, in particular, participate in photochemical reactions that lead to the formation of tropospheric ozone and secondary organic aerosols (SOAs), thereby degrading air quality and reducing atmospheric visibility (Li et al., 2023). The presence of these secondary pollutants has been linked to respiratory illnesses, cardiovascular stress, and overall ecosystem stress, especially in urban and peri-urban regions affected by landfill plumes.

Odorous emissions also contribute substantially to environmental degradation and psychosocial stress, particularly for communities located near landfills. Hydrogen sulfide (H_2S) and ammonia (NH_3), the most common sulfur- and nitrogen-based odorants, are not only strongly malodorous but also toxic at moderate concentrations. Hydrogen sulfide, even at sub-ppm levels, causes nausea, eye irritation, respiratory distress, and in extreme cases, neurological symptoms (Piccardo et al., 2022). Long-term exposure to these odorants, especially in poorly ventilated areas or regions with persistent wind stagnation, has been associated with increased rates of respiratory diseases, mood disturbances, and community-level nuisance complaints (Fang et al., 2012).

Recent studies underscore the significance of landfill leachate treatment plants (LLTPs) as critical VOC emission hotspots. A comparative investigation by Li et al. (2024) of two LLTPs in northern (NLF) and southern (SLF) China demonstrated notable differences in emission profiles and associated health risks. Across all samples, a total of 49 VOCs were detected, with emissions being highest in the oxidation ditch (OD) sections, particularly at the SLF site. In SLF-OD, the total VOC concentration reached a staggering 83,317.7 μg/m³, with dominant compounds including acetophenone, trichloroethylene, 2-butanone, and styrene. These emissions were composed primarily of oxygenated compounds, which accounted for over 70% of total VOC mass, followed by aromatics, chlorinated hydrocarbons, and nitrogen-containing species.

The study also assessed the ozone formation potential (OFP) of these emissions—a key indicator of photochemical reactivity. The SLF-OD exhibited an OFP of 189.12 mg/m³, more than double the 84.82 mg/m³ observed at the NLF-OD. This elevated reactivity reflects the higher abundance of volatile precursors and the warmer, more humid climate of the southern region, which together promote enhanced photochemical transformation and ozone generation. These findings reveal a geographic disparity in emission behavior and environmental burden, reinforcing the necessity of region-specific mitigation strategies.

Moreover, the health risk assessments conducted in the same study revealed elevated chronic toxicity and carcinogenic risks associated with SLF emissions. Compounds such as trichloroethylene, benzene, and 1,3-butadiene exceeded the hazard index (HI) thresholds and cancer risk benchmarks established by the U.S. Environmental Protection Agency (EPA), indicating a substantial public health threat to both landfill workers and nearby residents. The SLF site, due to its climatic and operational characteristics, exhibited higher levels of microbial activity, more complex leachate composition, and consequently greater VOC emissions and associated risks. These results underscore the urgent need for enhanced emission monitoring, gas treatment systems, and exposure reduction measures, particularly in warm and humid regions where landfill emissions are intensified.

Considering the above, the toxicological and environmental burden of VOCs and odorous emissions from landfills is both compound-specific and site-specific, influenced by local waste properties, environmental parameters, and operational practices. The cumulative effects of these emissions—ranging from direct health hazards to long-range atmospheric pollution—necessitate a holistic emission management approach that integrates chemical monitoring, health risk assessment, and site-specific engineering controls to protect environmental quality and human health.

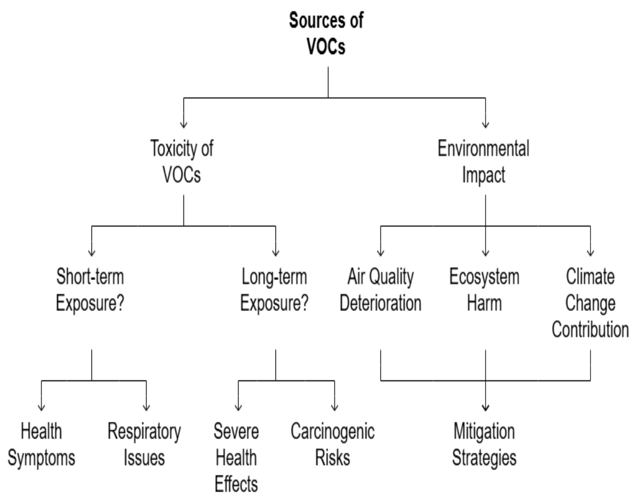

Figure 3: Key Environmental and Operational Factors Influencing VOC and Odorous Emissions from Landfills

4.6. VOC and Odor Emissions and Their Specific Health Impacts

Human exposure to volatile organic compounds (VOCs) and odorous compounds emitted from landfills occurs primarily through inhalation, but also via dermal contact and indirect ingestion, particularly among workers and nearby residents. Among these, inhalation is the most critical pathway due to the volatile nature of the compounds and their ease of dispersion in the atmosphere (Li et al., 2023b). In the course of this study, it became evident that landfill sites emit a complex array of volatile organic compounds (VOCs) and odorous gases originating from the microbial degradation of organic waste, chemical residues, and leachate volatilization. These emissions pose both olfactory nuisance and a spectrum of health risks, ranging from acute symptoms such as irritation and nausea to chronic effects like cancer and neurological disorders. The identification and impact analysis of major compounds including ammonia, hydrogen sulfide, benzene, toluene, trichloroethylene, and 1,3-butadiene were central to this assessment. (see Figure 4)

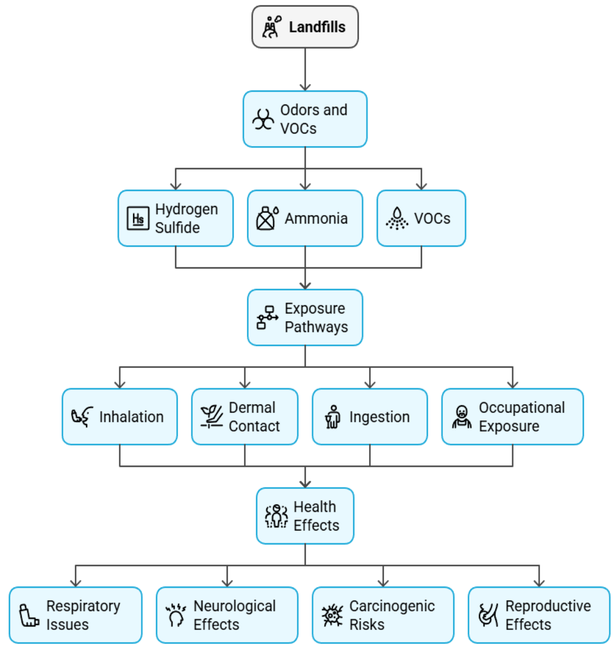

Figure 4: Exposure Pathways and Health Effects of VOCs and Odorous Compounds Emitted from Landfills

During my review and synthesis of the literature, (see Table 1) I found that ammonia (NH_3) and hydrogen sulfide (H_2S) were consistently reported as the most prevalent odorous emissions in landfill environments (Wang et al., 2021; Piccardo et al., 2022). These compounds, though often below occupational threshold limits, can significantly reduce environmental quality and public well-being. Particularly, H_2S due to its extremely low odor threshold is detectable by smell even at 0.0001 mg/m³ and has been associated with eye irritation, nausea, and headaches (Fang et al., 2012). My own observation is that odor perception frequently acts as a community-based early warning system, and the psychological impact of persistent foul odors should not be underestimated, even if toxicological levels are low.

Other sulfur-based odorants, such as methanethiol, dimethyl sulfide (DMS), and dimethyl disulfide (DMDS), were also detected in measurable concentrations (up to 1 mg/m³) in leachate storage pools and dumping areas. These compounds, although less toxic than VOCs like benzene, were observed to cause short-term discomfort, dizziness, and mucosal irritation (Pan et al., 2023; Li et al., 2023a). Given their high odor activity values (OAVs), these substances contribute disproportionately to the overall odor intensity and are a major source of public nuisance and worker complaints, which I believe must be more carefully addressed in current landfill management practices.

From a toxicological standpoint, the most concerning VOCs identified were benzene, 1,3-butadiene, styrene, and trichloroethylene (TCE). In several of the studies reviewed, benzene was present at concentrations as low as 0.003 mg/m³ and still posed a definite carcinogenic risk, particularly linked to leukemia and central nervous system damage (Wang et al., 2021; Li et al., 2023a). TCE, commonly found in dry cleaning residues and degreasers, was detected up to 1.5 mg/m³ and classified as a Group 1 carcinogen, capable of inducing kidney and liver cancer with long-term exposure (Fang et al., 2012). In my view, the fact that these compounds can persist even in regulated landfills suggests a need for real-time air quality monitoring and stricter industrial waste segregation at the landfill intake stage.

Interestingly, probabilistic modeling in a study from Beijing highlighted that ethylbenzene, benzene, chloroform, and 1,2-dichloroethane can exceed cancer risk thresholds (1×10^{-6}) not only for landfill workers but also for residents living within a 200–3,000 meter radius, especially under unfavorable meteorological conditions (Li et al., 2023b). This highlights a critical gap in current buffer zone regulations, which often do not account for extreme dispersion scenarios. My recommendation would be to re-evaluate buffer distances based on localized dispersion modeling and site-specific risk analysis.

In terms of non-carcinogenic effects, compounds like ammonia, toluene, xylene, acetone, and ethanol were frequently linked to respiratory tract irritation, neurotoxicity, and liver/kidney damage (Du et al., 2014; Pan et al., 2023). While their cancer risk may be lower, their widespread occurrence and synergistic effects particularly in poorly ventilated environments should not be ignored. Toluene and xylene, for example, are known to impair the central nervous system and have been associated with developmental toxicity when exposure occurs over extended periods (Fan et al., 2025).

Eye-related effects were also reported in several studies. Compounds like formaldehyde, benzene, ethyl acetate, and PAHs were found to affect the ocular system by causing conjunctival inflammation, tear film instability, and even corneal epithelial damage, particularly among sensitive populations such as the elderly and children (Yang et al., 2023; Jacob et al., 2005). This was an unexpected yet significant finding, highlighting that VOCs impact more than just the respiratory and nervous systems—they also contribute to ocular disease burden, an area that warrants further public health research.

Moreover, my interpretation of the literature suggests that occupational health is still an under-addressed area. Despite the availability of data indicating that landfill workers are exposed to the highest VOC concentrations, on-site risk mitigation remains minimal in many developing countries. Use of personal protective equipment (PPE), temporary cover systems, and gas extraction infrastructure should be mandated and consistently maintained, not just installed.

Finally, there is a pressing need to integrate health risk assessments (HRAs) with odor monitoring systems in routine landfill management. As observed in multiple studies, there is often a disconnect between what is considered “safe” from a chemical standpoint and what is perceived as harmful by local residents (Piccardo et al., 2022). Therefore, both quantitative (cancer slope factor, HQ) and qualitative (odor annoyance, quality of life) indicators should be combined to produce a holistic risk profile that informs policy decisions, zoning regulations, and public communication strategies.

While the chemical and toxicological understanding of landfill emissions continues to evolve, it is equally crucial to explore emerging technologies that can strengthen predictive capabilities and enhance response strategies for health protection. In this context, the integration of advanced computational tools offers a new frontier for emission monitoring and environmental risk assessment.

4.7. AI Driven Analysis of VOC and Odor Emissions from Landfills with a Focus on Large Language Model Integration for Emission Prediction and Health Risk Assessment

From my perspective, the integration of artificial intelligence (AI) based modeling and large language models (LLMs) presents a transformative opportunity for advancing the monitoring and assessment of VOC and odor emissions in landfill environments. Traditional field sampling and dispersion modeling methods, while valuable, are often limited by temporal resolution, resource demands, and sensitivity to fluctuating environmental variables.

In contrast, AI-driven systems particularly LLMs trained on comprehensive datasets including environmental monitoring records, toxicological profiles, and meteorological data can help bridge these gaps. These models can predict emission behavior, identify high-risk compounds, and assist in real-time health risk assessments. For instance, LLMs may automate the interpretation of complex VOC datasets, conduct probabilistic cancer risk analysis, and generate dynamic exposure maps when integrated with GIS and atmospheric models.

Furthermore, such AI-enhanced platforms can support environmental management by simulating the outcomes of different mitigation strategies and identifying the most effective pathways for emission control. In my view, future landfill emission control systems should incorporate these intelligent tools into a broader decision support framework to enhance environmental policy-making, improve risk communication, and protect public health with greater precision and adaptability.

5. Conclusions

This review synthesized current scientific knowledge on the emission characteristics, influencing factors, and health risks associated with volatile organic compounds (VOCs) and odorous substances emitted from landfills. The findings confirm that emissions are both chemically diverse and spatially variable, arising primarily from microbial degradation of organic waste and volatilization of chemical residues in leachate and solid waste. Among the most hazardous compounds identified were benzene, 1,3-butadiene, and trichloroethylene, which pose definite carcinogenic risks, while odorants such as hydrogen sulfide and ammonia were found to significantly affect quality of life and contribute to acute respiratory symptoms despite lower toxicological severity.

Key determinants of emission behavior include waste composition, microbial activity, cover system integrity, and climatic conditions, with leachate storage pools (LSPs) and dumping areas (LDAs) identified as primary emission hotspots. Notably, landfills located in warmer and more humid climates exhibited higher concentrations and a wider diversity of VOCs, emphasizing the role of regional environmental factors in emission profiles. Probabilistic dispersion modeling further revealed that exposure risks can extend well beyond 1,000 meters, suggesting that current buffer zone regulations may inadequately protect nearby communities.

From a public health perspective, the most vulnerable populations include landfill workers and residents within a 2–3 km radius, particularly under unfavorable meteorological conditions. Despite this, occupational health protection remains insufficient, especially in developing countries, where the use of PPE, health screening, and ventilation infrastructure is often lacking.

Policy Recommendations:

- **Revise buffer zone regulations** using site-specific dispersion modeling and probabilistic risk assessments to account for regional meteorological variability.
- **Mandate occupational exposure monitoring** and **protective measures** (e.g., PPE, gas capture systems) at all active landfill sites.
- **Enforce segregation of industrial and hazardous wastes** at intake points to prevent emissions of chlorinated VOCs and known carcinogens.
- **Implement real-time ambient air monitoring systems** integrated with odor activity value (OAV) analysis to address both chemical safety and community odor complaints.

Research Recommendations:

- **Further field-based studies** should quantify long-term exposure impacts across different demographic groups, especially in low-income communities.
- **Development of AI-driven decision support systems** is encouraged to predict emission behavior, simulate intervention scenarios, and guide adaptive landfill management.
- **Interdisciplinary studies** linking toxicological data with sensory analysis and psychosocial impacts will enhance the comprehensiveness of health risk assessments.

In conclusion, a multi-dimensional, risk-informed landfill management framework is urgently needed one that combines chemical monitoring, health-based regulation, and AI-enhanced modeling tools. By embracing this integrated approach, stakeholders can more effectively mitigate the environmental and health burdens posed by landfill emissions in a rapidly urbanizing world.

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