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UNRAVELLING THE LINK BETWEEN SOLID WASTE MISMANAGEMENT AND AIR POLLUTION - THE ROLE OF ENVIRONMENTAL FORENSICS

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1. INTRODUCTION

Open dumping and open burning are the primary waste treatment and disposal methods used in many developing countries (Ferronato & Torretta, 2019). Approximately 40% of the world's waste ends up in open dumpsites, especially in cities within middle and low-income countries that lack adequate waste collection and treatment systems. For instance, in many African cities, up to 90% of waste is openly dumped (United Nations Environment Programme, 2024). Even in cities where waste collection systems are well-established and offer extensive coverage, the lack of adequate treatment facilities and efficient processing systems often results in the collected waste being sent to landfills. Landfilling is linked to several environmental pollution issues, including (a) groundwater contamination from the leaching of organic, inorganic, and other harmful substances contained in the waste; (b) air pollution due to the suspension of particles and gaseous pollutants; (c) odour pollution affecting nearby communities; and (d) surface water pollution caused by potential runoff (Siddiqua et al., 2022). In addition, the accumulation of waste in landfills can pose long-term risks to public health and contribute to climate change, exacerbating health and environmental challenges globally.

From the air pollution perspective, in uncontrolled landfills and dump sites, waste can spontaneously combust due to factors like methane emissions from decomposing waste. Burning waste releases harmful carcinogens like dioxins, furans, and a short-lived climate pollutant, the black carbon, posing serious health risks. The combustion processes can also release polycyclic aromatic hydrocarbons (PAHs) and other volatile organic compounds (VOCs), further deteriorating the air quality. In recent years, the number of landfill fires has increased due to excessive heat, driven by climate change. From an environmental justice perspective, communities living near landfills are disproportionately exposed to severe air pollution and other attendant health and safety hazards. Growing awareness of these issues and the associated health impacts has led to a rise in citizens taking legal action, demanding cleaner air in cities, and raising the concerns of those living near waste dumpsites. However, there are no standard approaches, besides expensive real-time source apportionment tools, to understand the change in air quality levels attributable to waste dumping. The high cost associated with these tools makes legal redress a daunting task in developing countries.

Although, in a developing country context, in addition to poor waste management, sources like residential cooking and heating, transportation, and industries are also significant contributors to air pollution, actions are already in place to control emissions from these sectors. For example, in the case of residential cooking, several measures have been taken over the past few decades that have reduced exposure to household pollution (Health Effects Institute, 2024). In the case of transportation, we have vehicular emission standards in place, and for industries, we have industrial emission standards. However, waste management is an area yet to be addressed from an air pollution perspective and hence merits a calibrated strategy to address the issue. Despite the substantial impact of waste mismanagement on air pollution, strategies specifically addressing this issue have not received adequate attention in the past. Environmental forensics, as a techno-legal approach, has an important role to play in this situation.

2. THE ROLE OF ENVIRONMENTAL FORENSIC TOOLS

Environmental forensics in air pollution is used to identify pollution sources, track pollutant dispersion, assess environmental and health impacts, and quantify the

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damages. The goal is to determine who is responsible for the pollution, assess the extent of environmental damage, and support legal or regulatory actions (Abdul Samad et al., 2020). Environmental monitoring plays a critical role in environmental forensic investigations. There are two primary approaches to environmental monitoring: one, the conventional air quality monitoring methods, or reference techniques, established by federal or state agencies. These monitoring methods are typically available for a limited range of pollutants. In developing countries, courts often rely on these standardised methods to assess pollutant releases. However, this practice has sometimes proven to be a limitation, as investigations are restricted to the pollutants listed by federal agencies, leaving other potentially harmful substances unexamined. The second approach is to look for chemicals that can act as fingerprints of the sources of pollution. This approach often requires monitoring at the potential sources (for emission inventorization) and the receptor locations. The monitoring data along with appropriate modelling tools (dispersion/receptor) help to identify the sources, their relative contribution, and the time of release.

The first approach can be implemented by installing ambient air quality monitoring systems in landfill sites. Such systems can detect a range of harmful substances, including volatile organic compounds (VOCs), particulate matter, and greenhouse gases like methane. Several developed countries have made it mandatory to monitor air quality in landfill sites. However, this is not a common practice in developing countries. Moreover, when there are other possible sources for the monitored pollutants, establishing the contribution of landfills can be controversial.

The second approach involves using techniques like fingerprinting and modelling, where specific compounds act as indicators for various decomposition processes in landfills. For instance, methane serves as a fingerprint for anaerobic decomposition of organic waste, while hydrogen sulphide indicates the breakdown of sulphur-containing materials. Ammonia is a marker for the decomposition of nitrogenous organic matter. Specific pollutants like siloxanes point to the degradation of personal care products, medical waste, and other silicone-based materials. Compounds like polychlorinated biphenyls (PCBs), dioxins, and furans are linked to emissions from the breakdown of certain plastics, electrical components, and industrial waste. Further, the studies by Bakkaloglu et al. (2021, 2022) point to the possibility of using the difference in carbon isotopic signature of methane (CH_4) emitted from landfills of different ages to identify the specific landfill contributing CH_4 to the atmosphere. Landfill fires are not uncommon, and the use of compounds emitted during the fire incidents can serve as signatures for identifying the areas affected by these events. For instance, Polybrominated diphenyl ethers (PBDEs) were used as a signature compound to identify the areas within the city impacted by emissions from a major landfill fire in Santiago, Chile (Pozo et al., 2023).

Air pollution models are useful for quantifying emissions, identifying pollutant sources, and assessing health impacts from landfills. By inputting data on waste composition, decomposition rates, and other site-specific parameters, the emission models can estimate the rate of pollutants emitted. For example, the LandGEM (Landfill Gas Emissions Model), developed by the United States Environmental Protection Agency (USEPA), uses first-order decay equations to estimate emissions of methane and other gases from landfills based on waste acceptance data (United Nations Environment Programme, 2005). This model is used to calculate emission rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds, and specific air pollutants from municipal solid waste (MSW) landfills.

Source apportionment models are valuable for assessing the impact of landfill emissions on local air quality by determining the proportion of pollutants originating from landfills using techniques such as fingerprinting. This knowledge is crucial in understanding the potential health risks associated with landfill emissions, including respiratory and cardiovascular diseases, and consequently in liability allocation.

Dispersion modelling tools predict how landfill emissions move through the atmosphere. Gaussian dispersion models, such as AERMOD, consider meteorological data (e.g., wind speed, direction, temperature), landfill topography, and surrounding land use to simulate pollutant dispersion patterns (Perry et al., 2005).

These approaches discussed above are not just relevant for the forensic applications but also for the regular air quality management efforts as discussed below.

i) Compliance with national standards: National Ambient Air Quality Standards (NAAQS) is a legal tool available in the majority of the countries, and the states or provinces are mandated to take necessary steps to maintain these standards. However, in developing countries, the exceedance of these standards is very common. There are provisions under the Air Acts to monitor the NAAQS, but there is no way to identify the sectors or activities contributing to it on a day-to-day basis. Enhanced monitoring can identify pollution-causing activities at landfills and support mitigation strategies. Air quality models, such as AERMOD recommended by the USEPA, are vital for demonstrating regulatory compliance. Developing countries can use these models to assess landfill impacts and ensure emissions stay within limits, aiding the permitting process. These tools help operators and regulators make informed decisions to protect public health and the environment.

ii) Community exposure and health assessment: Although not a replacement for exposure monitoring, ambient air monitoring can provide a reasonable estimate of pollutants in the breathing zone. Thus, it reflects the community's exposure to air pollution. However, in developing countries, ambient air quality monitoring data near landfill sites is very limited. Even in developed countries, air quality monitoring (AQM) can be spatially limited, potentially failing to adequately represent the impact if they are not positioned downwind of the landfill. Mobile AQM stations can be used to fill in the gaps; however, due to their high cost, they cannot significantly increase spatial sampling density. Any lack of data can hinder the ability to accurately assess community exposure and implement effective health interventions for the communities living in the close vicinity of a landfill site. A cost-effective approach for AQM would be the establishment of mixed networks including both reference-grade monitors as well as emerging sensor technologies (Gani et al., 2022). Further, dispersion model predictions help in identifying areas at higher risk of exposure to harmful pollutants, establishing buffer zones around landfills, and strategically placing monitoring stations.

iii) Intervention assessment: Assessing the effectiveness of interventions at landfill sites to reduce pollution is often challenging. Installing air quality monitors would help determine which measures have been successful and which have not. Dispersion models are used to evaluate the effectiveness of various mitigation strategies, such as gas collection systems, flaring, and biocovers. By simulating scenarios with and without these measures, models can provide quantitative assessments of emission reductions.

3. THE IMPORTANCE OF REGULATORY SUPPORT

In developed countries, environmental forensics is being utilized to ensure that environmental regulations are strictly adhered to and hold polluters accountable for air pollution caused by waste mismanagement. In the European Union, directives such as the Waste Framework Directive and the Ambient Air Quality Directive mandate the member states to ensure comprehensive monitoring and reporting of emissions from various waste management facilities, including landfills. These directives require member states to implement national laws and strategies that ensure continuous air quality monitoring and enforce strict penalties for non-compliance. In response, local authorities are driven by national legislation to adopt environmentally sound practices of waste management.

On the other hand, environmental regulators in developing countries have to contend with deficiencies in legislative framework and state capacity. For instance, in India, air pollution is regulated under the Air Act, and waste is managed under the Environmental Protection (EP) Act and different rules, including municipal, plastic waste, biomedical, hazardous, e-waste, and construction waste management rules. Under the Biomedical Waste Management Rules, it is mandated to install air quality monitors in biomedical waste processing centers across the country. Yet, these rules are unevenly implemented. Even rights-conscious judicial interventions for upgrading enforcement capacities could produce only mixed outcomes (Gill, 2024). Furthermore, India's air pollution control legislation does not penalize local government officials for contravening their duties. Since municipal authorities are primarily responsible for solid waste management, there is a worrying gap in existing accountability mechanisms. Similar deficiencies in the legislative regime are compounded by structural limitations of local government, resulting in the release of toxic air pollutants on account of waste mismanagement. Thus, it is critical to harmonize the enforcement and penalty regimes under air quality and waste management laws. Under the provision of waste management rules and the Air Act, it can be mandated to install air quality monitors near landfills and dump sites, regularly monitor, and take necessary measures if it exceeds the NAAQS. For all other sources of pollution, it is possible to establish emission standards, but in the case of open landfills, this can be a suitable way, and the residents around the landfill will also be aware of the prevailing air pollution levels.

Effective accountability should involve not only penalizing immediate violations but also ensuring the implementation of robust waste management practices based on source segregation, efficient collection and scientific treatment and disposal, and regular air quality monitoring. This comprehensive approach is essential for addressing the environmental and public health impacts associated with landfill operations and for ensuring long-term improvements in waste management practices.

4. ENFORCEMENT

The effectiveness of environmental regulations is significantly compromised by the lack of a stringent penalty regime. In developing economies, including India, the enforcement of environmental laws related to waste management and air quality are restricted by inadequate penalty mechanisms. While penalties for specific episodic and visually evident violations, such as landfill fire outbreaks, are occasionally imposed by regulatory bodies or judiciary systems, regular issues, such as PM emissions from vehicular movement while transporting waste, ongoing smouldering of waste, and constant methane emissions from decomposing waste, often go unnoticed and unaddressed.

In addition to air monitoring, critical preventive measures designed to minimize air pollution and reduce landfill fire hazards need to be enforced. These measures include daily compaction of waste using dozers and covering waste with a layer of soil or debris of sufficient thickness to prevent exposure to the environment. These practices are intended to control emissions, prevent fires, and manage waste more effectively. However, compliance with these protocols is often lacking in developing countries, leading to poorly managed sites that do not adhere to scientifically sound operational standards. This gap in compliance highlights the urgent need for robust accountability mechanisms for municipal government and waste generators.

5. CONCLUSIONS

Developing countries face significant challenges with solid waste management and air pollution. Ineffective waste management practices, such as open dumping and burning, significantly contribute to air pollution. Despite the clear link between waste mismanagement and air pollution, targeted strategies to address this issue have often been overlooked. Environmental forensics, which includes tools such as monitoring, modeling, and fingerprinting, plays a crucial role in this context. These techniques can help identify emission levels, sources, and timing of emissions. To effectively tackle the issue of air pollution from waste management practices, it is essential to align enforcement and penalty measures across air quality and waste management regulations. Environmental forensics has a significant supporting role to play in this.

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