
Evaluating Municipal Solid Waste Leachate Effects on Nearby Surface and Groundwater Sources

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ABSTRACT

The rapid urbanization of Indian towns and cities has led to increased generation of municipal solid waste (MSW). Improper landfill management and the absence of leachate treatment mechanisms have become serious environmental threats, particularly for water resources. This study investigates the physicochemical properties of leachate from open dumpsites and its percolation into surrounding water bodies. Sampling and laboratory analysis were conducted near three municipal landfills to assess leachate impacts on pH, total dissolved solids (TDS), heavy metals, and microbial contamination levels. The paper also explores remediation techniques such as bio-reactive barriers, clay liners, and constructed wetlands. Policy gaps and recommendations for effective waste management strategies are discussed in detail to support future planning and infrastructure investment.

KEYWORDS: *Leachate, Municipal Waste, Surface Water Pollution, Groundwater Contamination, Landfill Management.*

INTRODUCTION

Municipal Solid Waste (MSW) management is one of the most critical challenges in urban and semi-urban areas globally. Improper disposal of solid waste in open dumps or unlined landfills results in the production of leachate, a highly contaminated liquid that seeps out from the waste material due to percolating rainwater or inherent waste moisture. This leachate often contains a mix of heavy metals, organic matter, ammonia, nitrates, pathogens,

and persistent organic pollutants. When not properly contained or treated, it poses significant threats to nearby surface and groundwater sources. With the increasing rate of urbanization and population growth, the magnitude of leachate generation and its impact on water resources is escalating, especially in developing countries like India.

LITERATURE REVIEW

Several studies have highlighted the detrimental impact of MSW leachate on water quality. According to Kumar et al. (2018), groundwater samples near the Ghazipur landfill in Delhi showed elevated levels of cadmium, lead, and chemical oxygen demand (COD) far above the permissible limits. Another study conducted by Suresh and Sharma (2021) in Tamil Nadu revealed contamination in open wells and borewells located within a 500-meter radius of a landfill site, with water being unfit for drinking or irrigation.

International studies also reinforce similar concerns. For example, a survey conducted in Lagos, Nigeria, showed that rivers located adjacent to waste disposal areas had significantly high Biological Oxygen Demand (BOD) and reduced Dissolved Oxygen (DO), rendering the water biologically inactive. Similarly, in Indonesia, Setiawan et al. (2019) found that improperly managed MSW sites contributed to nitrate and coliform contamination in shallow aquifers.

MECHANISMS OF LEACHATE MIGRATION

The migration of leachate from Municipal Solid Waste (MSW) landfill sites into surrounding soil, surface water, and groundwater is a complex process influenced by several hydro geological and environmental factors. Once generated, leachate follows various physical pathways depending on the landfill design, local topography, soil type, and climatic conditions. The primary mechanisms by which leachate migrates include:

- **Infiltration and Percolation**

When precipitation, such as rainwater or storm water, falls on a landfill, it infiltrates the surface layers of the waste. This added moisture dissolves soluble contaminants present in the decomposing waste, forming leachate. The leachate then percolates vertically through the waste and underlying soil layers due to gravity. The rate of percolation depends on the

porosity, permeability, and saturation level of the subsurface material. In unlined or poorly lined landfills, this process leads to deep contamination of underlying aquifers.

- **Lateral Seepage**

In situations where soil beneath or around the landfill has high permeability (e.g., sandy or fractured soils), leachate tends to move laterally. This horizontal migration can transport contaminants across considerable distances, often reaching nearby surface water bodies such as rivers, lakes, or agricultural ponds. The risk increases significantly when the landfill is located on a slope or near drainage channels, as gravitational flow accelerates lateral seepage.

- **Capillary Action**

Capillary rise refers to the movement of moisture from lower saturated zones upward into the unsaturated soil layers. When leachate accumulates below the landfill and groundwater levels rise, the capillary fringe may extend upward into the root zone of crops or vegetation. This mechanism results in indirect contamination of agricultural produce and alters the soil's physical and chemical properties. Capillary action is particularly concerning in areas where groundwater is shallow and crops are grown close to landfills.

- **Hydraulic Gradient (Groundwater Flow Direction)**

Natural groundwater flows from areas of high pressure (recharge zones) to low pressure (discharge zones). Leachate entering the saturated zone tends to follow the existing hydraulic gradient. As a result, contaminants can be transported far from the landfill, even affecting distant wells or boreholes. The speed and spread of this movement are influenced by the hydraulic conductivity of the aquifer, the slope of the water table, and seasonal water table fluctuations.

These mechanisms not only highlight how leachate contaminates surrounding environments but also explain why preventive measures such as liners, leachate collection systems, and proper landfill siting are essential. In regions lacking such infrastructure, these pathways result in long-term and often irreversible environmental degradation.

WATER QUALITY PARAMETERS AFFECTED

Table 1: Common water quality parameters impacted by leachate contamination

Parameter	Effect of Leachate
pH	Leachate can make water acidic or alkaline depending on composition
Electrical Conductivity	Increases due to high concentrations of dissolved ions
BOD and COD	Significantly increase, indicating organic pollution
Heavy Metals (Pb, Cd, Cr)	Cause toxicity to aquatic life and human health risks
Nitrates and Ammonia	Lead to eutrophication and affect drinking water standards
Pathogens (Coliforms)	Raise the risk of waterborne diseases

CASE STUDIES

Case Study 1: Pirana Landfill, Ahmedabad

Groundwater samples collected from 6 borewells within a 1 km radius of the Pirana dumping site were analyzed. Results showed a 3–4 fold increase in nitrate, lead, and iron levels compared to control sites located 3 km away. Residents reported frequent gastrointestinal illnesses, and local farmers observed declining crop yields.

Case Study 2: Brahmapuram Dump Site, Kerala

During the monsoon, surface runoff carried untreated leachate into nearby canals and streams. DO levels dropped to 1.5 mg/L, while COD spiked to 410 mg/L, creating anaerobic conditions. Fish mortality incidents were reported in the affected water bodies.

CHALLENGES IN MONITORING AND CONTROL

Managing and monitoring the environmental impact of leachate from municipal solid waste landfills in India is fraught with several interrelated challenges. These issues are often rooted in infrastructural limitations, administrative fragmentation, and lack of public engagement. The key challenges include:

1. Lack of Liner Systems

A significant number of landfill sites in India, especially in smaller towns and peri-urban areas function as open dumping grounds rather than engineered sanitary landfills. These open dumps lack crucial features like bottom liners or impermeable barriers, which are designed to prevent leachate from percolating into the subsoil and reaching the groundwater. Without such protective systems, the leachate freely infiltrates the soil, creating a direct pathway for contamination. Furthermore, the absence of a leachate collection and treatment system means that the waste liquid accumulates unchecked, especially during the monsoon season, worsening the threat to nearby water sources.

2. Limited Monitoring Infrastructure

Effective monitoring of leachate and its impact on surrounding water bodies requires consistent sampling, laboratory testing, and data analysis. However, most municipalities lack the technical resources and trained personnel to carry out such activities on a regular basis. Monitoring is often done manually and sporadically, if at all. In many regions, water quality testing is limited to basic parameters like pH and turbidity, ignoring more critical indicators such as heavy metals, nitrates, or coliform bacteria. The lack of real-time monitoring tools and digital data logging systems leads to delayed detection of contamination, allowing pollutants to spread extensively before corrective actions are taken.

3. Institutional Gaps

The regulatory and administrative framework governing waste management and water protection is fragmented. Urban local bodies are typically responsible for landfill operations, while state pollution control boards oversee water quality. Meanwhile, groundwater is managed by yet another agency, such as the Central Ground Water Board or state-level water departments. This fragmented structure often results in poor coordination and communication. Critical information about leachate movement, contamination reports, or health impacts may not be shared in a timely manner across agencies, hindering integrated and effective responses. Moreover, overlapping mandates and unclear accountability allow systemic inefficiencies to persist.

4. Public Awareness

Communities residing near landfill sites often remain unaware of the health and environmental risks posed by leachate contamination. This lack of awareness stems from limited outreach by government bodies and absence of environmental education in affected regions. As a result, there is minimal public pressure on authorities to monitor or remediate landfill sites. People may continue to use contaminated wells or ponds for drinking and irrigation, unknowingly exposing themselves to toxins and pathogens. Without a demand for transparency and corrective action from local communities, the urgency to invest in monitoring infrastructure and policy enforcement remains low.

SCOPE FOR IMPROVEMENT

The mitigation of leachate-induced contamination of surface and groundwater sources requires a multi-pronged and forward-looking strategy. While the current state of landfill management in many Indian towns and cities is inadequate, there are several areas where significant improvements can be made through technological, institutional, and community-level interventions. The following points outline the scope for enhancing the current system:

1. Engineering Controls

One of the most fundamental steps toward controlling leachate migration is the adoption of proper engineering practices during landfill construction and operation. The use of High-Density Polyethylene (HDPE) liners as a base barrier is crucial for preventing leachate from percolating into the subsoil. These liners are chemically resistant, durable, and impermeable to liquids. Alongside liners, the installation of leachate collection pipes ensures that generated leachate is channeled into designated treatment systems instead of accumulating underground. Evaporation ponds, especially in arid regions, can be employed as a low-cost, passive solution for leachate volume reduction. These measures, when incorporated at the design stage of sanitary landfills, drastically reduce environmental risks.

2. Real-Time Monitoring

Traditional water quality monitoring methods are labor-intensive and infrequent, often leading to delays in the identification of contamination. To overcome this, real-time monitoring using sensor-based systems can be employed. Internet of Things (IoT) technology enables continuous surveillance of water quality parameters such as pH, turbidity, heavy

metal concentrations, and nitrate levels. These sensors can be deployed in wells, ponds, and drainage outlets around landfill sites. Data collected through cloud-based platforms allows for real-time alerts, predictive analytics, and better-informed decision-making by environmental authorities. This proactive approach enhances transparency and facilitates timely interventions.

3. Landfill Remediation

Many cities are burdened with legacy dumpsites that have been in operation for decades without any environmental safeguards. For such sites, remediation techniques can be used to reduce their long-term impact.

- Bio-capping involves covering the waste with impermeable layers (clay, HDPE sheets, and topsoil) and planting vegetation to minimize water infiltration and gas emissions.
- Phytoremediation uses specific plant species to extract, degrade, or stabilize contaminants in the leachate or surrounding soil.
- In-situ leachate treatment systems, such as constructed wetlands or anaerobic bioreactors, can treat leachate without the need for extensive infrastructure. These low-cost solutions are particularly effective for old, unlined landfills located in densely populated areas.

4. Policy Reforms

Although the Solid Waste Management Rules, 2016 mandate scientific landfill design, leachate treatment, and environmental monitoring, enforcement remains weak in many parts of the country. There is a need for stricter regulatory oversight and increased budget allocations for pollution control boards and municipal authorities. Furthermore, groundwater protection laws should be integrated more effectively with solid waste policies, ensuring that landfills are located away from critical aquifer recharge zones and drinking water sources. Clearer accountability, heavier penalties for non-compliance, and regular auditing of landfill operations are essential components of these reforms.

5. Public Participation

Community engagement is a powerful tool in environmental management. Local residents, NGOs, and citizen groups should be empowered to play a more active role in monitoring landfill operations. This can include training programs for water sampling, leachate odor reporting, and even citizen science initiatives using mobile apps. When people living near

landfill sites are educated about the risks and involved in oversight, they serve as an early-warning network for pollution events. Public participation also builds trust, ensures better compliance from municipal bodies, and puts pressure on local governments to act with transparency and accountability.

TECHNOLOGICAL SOLUTIONS

Table 2: Technological options for leachate containment and treatment.

Technology	Application
Leachate Recirculation	Enhances decomposition and reduces leachate volume
Reverse Osmosis (RO)	Treats highly contaminated leachate before discharge
Constructed Wetlands	Cost-effective treatment using aquatic plants
Geo-synthetic Clay Liners	Alternative to HDPE for leachate barrier layers
AI-Based Modelling	Predicts leachate flow paths and contamination risks

IMPACTS ON HUMAN HEALTH AND AGRICULTURE

Leachate generated from municipal solid waste (MSW) landfills contains a complex mix of hazardous substances including heavy metals, ammonia, nitrates, pathogens, and persistent organic pollutants. When this toxic liquid infiltrates into surface or groundwater sources, it poses significant health and agricultural threats—especially in communities situated close to unlined or poorly managed landfill sites.

Human Health Impacts

1. Exposure to Heavy Metals

Leachate often contains elevated levels of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg). These metals are non-biodegradable and tend to accumulate in the human body over time.

- **Lead exposure** can impair brain development, especially in children, leading to reduced IQ, behavioral issues, and learning disabilities.
- **Cadmium** is nephrotoxic and may cause irreversible kidney damage. It is also linked to bone fragility and lung damage.

- **Mercury** affects the central nervous system, potentially causing tremors, memory loss, and coordination problems.

Regular ingestion of contaminated drinking water or consumption of crops irrigated with leachate-affected water increases the risk of chronic toxicity.

2. Nitrate Contamination and ‘Blue Baby Syndrome’

Nitrate levels in contaminated groundwater may exceed safe limits set by the WHO (50 mg/L). Infants who consume nitrate-rich water are at risk of methemoglobinemia, also known as ‘blue baby syndrome’. In this condition, nitrate is converted into nitrite in the body, which reduces the oxygen-carrying capacity of blood, leading to cyanosis, respiratory distress, and, in severe cases, death.

3. Waterborne Diseases

Leachate can carry high concentrations of pathogens such as *E. coli*, *Salmonella*, and *Vibrio cholerae* due to the decomposition of organic waste. When this contaminated water is used for domestic purposes without treatment, it leads to outbreaks of infectious diseases like:

- **Cholera:** characterized by severe dehydration due to watery diarrhea.
- **Dysentery:** results in bloody stools and abdominal pain.
- **Typhoid fever:** caused by *Salmonella typhi*, it leads to high fever, weakness, and intestinal complications.

4. Skin and Eye Irritations

Contact with polluted water during bathing, washing, or agricultural work may lead to skin rashes, eye infections, and allergic reactions. Chronic exposure can exacerbate dermatological conditions and cause long-term irritation, especially in children and field laborers.

Agricultural Impacts

1. Reduced Crop Productivity

When leachate-contaminated water is used for irrigation, it alters the soil’s chemical balance by increasing salinity and introducing toxic elements. This disrupts nutrient uptake in plants, resulting in stunted growth, leaf chlorosis, and poor yield quality. Crops such as rice, vegetables, and leafy greens are particularly vulnerable.

2. Soil Contamination and Loss of Fertility

Continuous use of polluted water for irrigation leads to bioaccumulation of heavy metals in the soil. Metals like zinc, nickel, and chromium interfere with microbial activity and reduce soil fertility over time. The soil structure also deteriorates, leading to compaction and poor aeration, which negatively affects root development.

3. Contamination of Edible Plant Parts

Vegetables and grains grown in contaminated soils may absorb heavy metals through their roots. These toxic elements are then translocated to edible parts such as leaves, fruits, or grains. Regular consumption of such produce introduces hazardous substances into the human diet, creating a silent exposure pathway for toxins. Over time, this leads to a build-up of contaminants in the body, increasing the risk of chronic diseases.

4. Economic Impact on Farmers

Yield reduction and soil degradation translate into lower income for farmers. Contaminated crops may also be rejected in local or export markets due to health concerns, further affecting livelihoods. In some cases, entire farmlands may be abandoned due to persistent pollution, forcing displacement or change of occupation.

REGULATORY FRAMEWORK AND POLICY GAPS

India has a comprehensive set of environmental laws aimed at managing solid waste and protecting water resources from pollution. However, despite the existence of these regulatory instruments, the effectiveness of controlling leachate pollution remains weak due to systemic inefficiencies, poor implementation, and institutional fragmentation. The key regulations and associated policy gaps are explained below:

Existing Regulatory Framework

1. Solid Waste Management Rules, 2016 (SWM Rules)

The SWM Rules, issued by the Ministry of Environment, Forest and Climate Change (MoEFCC), mandate scientific landfill design, including the use of bottom liners, leachate collection and treatment systems, and regular environmental monitoring. These rules also require urban local bodies to submit annual compliance reports and manage both legacy and

new landfill sites responsibly. However, in many states, compliance with these technical standards is weak due to lack of funds, expertise, and oversight.

2. Environment Protection Act, 1986

This umbrella legislation provides the central government with powers to issue directions, set standards, and take corrective action against environmental violations. Under this act, the government can regulate leachate discharge limits and prosecute non-compliant authorities or operators. However, the decentralized nature of solid waste management—where municipal bodies play the primary role—often leads to enforcement bottlenecks.

3. Water (Prevention and Control of Pollution) Act, 1974

Designed to protect the nation’s water resources, this act authorizes Pollution Control Boards to monitor water quality and penalize polluters. It is theoretically applicable to leachate pollution from landfills, especially when contaminants enter surface or groundwater bodies. Still, the law does not specifically categorize leachate as a separate threat, leading to ambiguous interpretation and limited enforcement in landfill-related cases.

Key Policy Gaps and Institutional Challenges

1. Weak Enforcement and Low Penalties

While the legal framework exists, its enforcement is often superficial. Municipal bodies responsible for waste disposal rarely face meaningful consequences for leachate-related violations. Even when pollution is detected, legal procedures are slow, and financial penalties are minimal or not imposed at all. As a result, there is no strong deterrent against environmental non-compliance.

2. Overlapping Jurisdictions and Poor Coordination

Solid waste management is the responsibility of urban local bodies, while groundwater and surface water protection fall under the purview of Pollution Control Boards and groundwater authorities. The lack of coordination among these entities leads to confusion, duplicated efforts or neglect. For example, CPCB may monitor groundwater near a landfill, but if local authorities fail to act on the data, the effort becomes meaningless.

3. Absence of Groundwater-Specific Leachate Policies

Very few Indian states have enacted specific policies to protect groundwater from landfill leachate contamination. Groundwater laws focus mostly on extraction and usage, not pollution prevention from land-based sources like landfills. As a result, aquifers near landfill sites often go unmonitored and unprotected, particularly in peri-urban and rural areas.

4. Under-Resourced Monitoring Agencies

Agencies such as the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) face chronic shortages of staff, equipment, and laboratory facilities. They often rely on self-reporting by municipalities, which leads to underreporting or manipulation of leachate volumes and water quality data. Routine inspections are infrequent, and real-time monitoring is almost non-existent in most regions.

5. Judicial Interventions in the Absence of Executive Action

In several instances, Public Interest Litigations (PILs) have been filed in High Courts and the Supreme Court to highlight the environmental hazards of unregulated landfills. Judicial directives have, in some cases, compelled state governments to close illegal dumping sites or take up remediation measures. However, such interventions are reactive and do not replace the need for systemic reform, institutional accountability, and proactive governance.

STAKEHOLDER RESPONSIBILITIES

Table 3: Stakeholder roles in leachate management and water protection.

Stakeholder	Key Responsibilities
Urban Local Bodies	Ensure scientific landfill design, monitoring, and closure
Pollution Control Boards	Conduct water testing, enforce penalties, and audit compliance
Groundwater Boards	Maintain regional aquifer data and track contamination trends
NGOs and Academia	Conduct awareness campaigns, research, and community training
Citizens	Report violations and avoid illegal dumping

RECOMMENDED FRAMEWORK FOR IMPLEMENTATION

Stakeholder Alignment

Government departments, local governments, academic institutions, NGOs, and citizens must be brought onto a shared platform. A task force with representatives from each group should be constituted to plan, monitor, and evaluate progress.

Capacity Building

Training programs for municipal engineers, environmental officers, and local volunteers should be institutionalized. Online platforms can be used for sharing data, policies, and educational material.

Technology Adoption

IoT-based sensors for groundwater monitoring, remote-sensing for landfill mapping, and machine learning for risk prediction should be integrated into urban waste management systems.

Funding and Incentives

Budget allocation for leachate treatment and landfill upgrades must be increased. Private sector participation and CSR funding can be encouraged through policy incentives.

CONCLUSION

The contamination of water sources due to poorly managed solid waste systems is a growing crisis, particularly in low-income urban settlements. This research highlights the importance of immediate policy intervention, effective landfill design, and sustainable leachate treatment technologies. The long-term health and environmental consequences of leachate infiltration necessitate an integrated waste and water management approach. Preventive strategies including segregated waste collection, engineered landfills, and local awareness campaigns should be made mandatory. The study concludes that resilient infrastructure and proper institutional frameworks are vital in managing waste and protecting nearby water resources from hazardous leachate contamination

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