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Leachate Management Challenges in O.R. Tambo District Municipality, South Africa

Lwanda Matiso[1*], Tom Okello[2]

[1] Department of Biological and Environmental Sciences, Walter Sisulu University, Private Bag X1, Mthatha 5117, Republic of South Africa
[2] Department of Geography, University of the Free State, Private Bag X13, Phuthaditjhaba 9866, Republic of South Africa

Corresponding Author Email: lmatiso@wsu.ac.za

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ABSTRACT

The formation of leachate at landfill sites poses a major environmental risk, particularly through the pollution of surface and groundwater. This study examines the challenges of leachate management in the O.R. Tambo District Municipality (ORTDM), South Africa. It examines infrastructure deficiencies, operational constraints and the feasibility of sustainable financing mechanisms. A qualitative research approach was utilized, including interviews, field observations and a review of academic literature, dissertations and online resources. Triangulation methods were used to validate the data. The results show serious inadequacies in leachate management in all five local municipalities (King Sabata Dalindyebo, Nyandeni, Ngquza Hill, Mhlontlo and Port St John's). In three municipalities, open dumping is still widespread due to a lack of basic landfill elements such as designated waste cells, ground covers and drainage systems. Only the municipalities of King Sabata Dalindyebo and Mhlontlo have limited infrastructure for leachate collection. Budgetary constraints are the main obstacle to improving landfill management. The lack of key infrastructure exacerbates the risk of water pollution. Historical incidents of leachate contamination emphasise the need for proactive intervention. The study examines future changes in waste composition and the potential of public-private partnerships in addressing funding challenges. Urgent investment in waste management infrastructure, stronger policy enforcement and community engagement are essential to mitigate environmental risks and ensure sustainable landfill operations in ORTDM.

1. INTRODUCTION

Leachate, the liquid produced when rainwater infiltrates a landfill and interacts with the decomposing waste, poses a serious threat to the environment as it can contaminate surface and groundwater resources [1]. This complex liquid is often rich in pollutants, including organic matter, heavy metals and various inorganic compounds, which can seriously affect the surrounding water resources and ecosystems if not effectively treated [2, 3]. The lack of adequate infrastructure in ORTDM exacerbates these risks, making effective leachate management critical to minimizing environmental damage.

The uncontrolled release of leachate into the environment poses a significant threat, including contamination of groundwater, surface water and soil, which can have serious consequences for public health and biodiversity [4, 5]. Consequently, the implementation of effective leachate management strategies is crucial for reducing the environmental impact of municipal solid waste landfills [6-8]. This study extends previous research by incorporating historical data on leachate pollution and assessing the long-term ecological impacts. In addition, future changes in waste composition and their impact on leachate management are considered.

The O.R. Tambo District Municipality (ORTDM) is situated on the east coast of South Africa's Eastern Cape Province and encompasses a diverse range of landscapes, from rolling hills to coastal plains [9]. With an area of approximately 15,947 km², the district encompasses the former Transkei Homeland and is characterized by a predominantly rural population, with approximately 93% of the population living in scattered homesteads and small villages [9]. The district consists of five local municipalities: King Sabata Dalindyebo (KSD), Nyandeni, Ngquza Hill, Mhlontlo and Port St John's [9].

Given the demographic and geographical diversity of the district, effective leachate management in ORTDM is particularly important. The area faces unique environmental challenges, including extensive agricultural activities and limited waste management infrastructure. In addition, socio-economic factors such as a high unemployment rate and low levels of education hinder effective waste management. Leachate formation is a natural process that occurs when rainwater permeates the waste layers in a landfill and triggers a cascade of physical, chemical and biological reactions that mobilize pollutants. The volume and composition of leachate is influenced by factors such as the rate of water infiltration, the type of waste and the age of the landfill.

Investigating the state of leachate management at ORTDM sheds light on local environmental issues and serves as a case

study for understanding common challenges faced by rural communities in South Africa. This study examines historical incidents of leachate contamination and highlights the cumulative environmental damage over time. It also examines how the evolution of waste composition due to changing consumer habits and industrial activities could affect future leachate management needs.

This study aims to answer the following research questions: What leachate management practices are in place at landfills in ORTDM and how effective are they in preventing pollution? What key factors influence the generation, composition and variability of leachate in the context of ORTDM? What treatment and disposal practices are currently used for leachate and how are these compatible with the principles of sustainable waste management? How can technological advances and best management practices be integrated into existing leachate management systems to improve environmental protection?

This study provides an overview of the state of leachate management in municipal solid waste landfills within ORTDM, focusing on the factors that influence leachate generation and current treatment methods. Potential future developments in leachate management will also be explored, focusing on recent technological advances and sustainable practices. New technologies such as membrane filtration, advanced oxidation processes and biological treatments offer promising solutions to improve leachate treatment outcomes [10, 11]. For example, membrane filtration has proven its effectiveness in removing organic and inorganic pollutants, while advanced oxidation processes degrade persistent organic pollutants. In addition, biological treatment methods utilize microorganisms to degrade pollutants and offer an environmentally friendly approach to leachate treatment [10].

In addition, the implementation of sustainable practices, including waste segregation and the development of bioreactors within landfills, has the potential to reduce leachate generation and improve treatment options [12]. Bioreactors facilitate the biodegradation of organic material in landfills, resulting in lower leachate production and a more controllable leachate composition [12]. Understanding the factors that influence leachate formation, and the effectiveness of current treatment methods is crucial for the development of sustainable and efficient leachate management strategies. By advancing research into innovative technologies, introducing best waste management practices and implementing sustainable approaches, the environmental risks associated with landfill leachate can be significantly reduced.

2. MATERIALS AND METHODS

A qualitative research approach was used to assess leachate management practices at landfill sites in the O.R. Tambo District Municipality, South Africa, as shown in Figure 1. This approach provided deep insights into complex social and environmental practices that go beyond quantitative measurements [13]. Semi-structured interviews, field observations and document analyses were conducted. Triangulation ensured the validity of the data by comparing interview responses with documentary evidence and observations. Historical incidents of leachate contamination were identified through municipal records and literature searches to improve understanding of past challenges and responses in leachate management.

2.1 Study area

The O.R. Tambo District Municipality (ORTDM) is on the east coast of South Africa's Eastern Cape Province, bordering the Indian Ocean. It borders several other districts, including Alfred Nzo to the north, Joe Gqabi to the northwest, Chris Hani to the west and Amathole to the southwest. It also borders the province of KwaZulu-Natal to the north-east. The area includes the former Transkei Homeland and stretches along the Wild Coast, a region known for its rugged beauty and diverse natural landscapes [9].

ORTDM covers an area of approximately 15,947 km² and is characterized by a diverse landscape that includes hilly valleys, mountain ranges and coastal plains. The district's climate is influenced by its topography and proximity to the coast, resulting in a variety of microclimates. ORTDM consists of five local municipalities: King Sabata Dalindyebo (KSD), Nyandeni, Ngquza Hill, Mhlontlo and Port St John's. The district is categorized as a C2 municipality, which indicates a predominantly rural population, as about 93% of residents live in rural areas [9].

2.1.1 Climate

The climate in ORTDM varies significantly due to differences in altitude and distance from the coast. Average temperatures range from a minimum of 14.3 – 19.8°C in summer to 1.8 – 13.4°C in winter, with maximum averages of 14.3 – 25.3°C in summer and 19.5 – 21.4°C in winter. Coastal regions generally receive more than 800 mm of rainfall annually, while rainfall in the interior, especially in larger river valleys, decreases steadily. In coastal areas, precipitation occurs even during the winter months, while approximately 80% of the rainfall in the interior falls between October and March. These climatic fluctuations significantly impact agricultural practices, water availability, and the livelihoods of local communities [9].

2.1.2 Population spatial density patterns

Population distribution within ORTDM is uneven, with a higher concentration in the western part of the district, particularly around the main urban center, Mthatha. The most populous municipality is KSD, home to approximately 429,233 residents, accounting for 29% of the district's total population, with a population density of 142 inhabitants per square kilometer. In contrast, Port St. John's, located about 100 kilometers to the east, is the next most densely populated area, with a density of 118 inhabitants per square kilometer.

There is a noticeable trend of migration toward urban centers as individuals seek employment opportunities and better living conditions. Despite its relatively high population density, the ORTDM is considered overpopulated; however, this classification depends on various factors, including housing quality, infrastructure capacity, and access to urban services. Over the last decade, population growth in the region has declined, with an average annual growth rate of 0.5% between 1996 and 2007, significantly lower than the national rate of 2.7%. The Integrated Development Plan (IDP) for 2006–2007 recorded a negative growth rate of -0.3%, attributed to high migration rates driven by economic challenges, poor living conditions, and the prevalence of health issues such as HIV/AIDS and tuberculosis. Future projections indicate that the population is likely to continue declining if these challenges are not addressed [14].

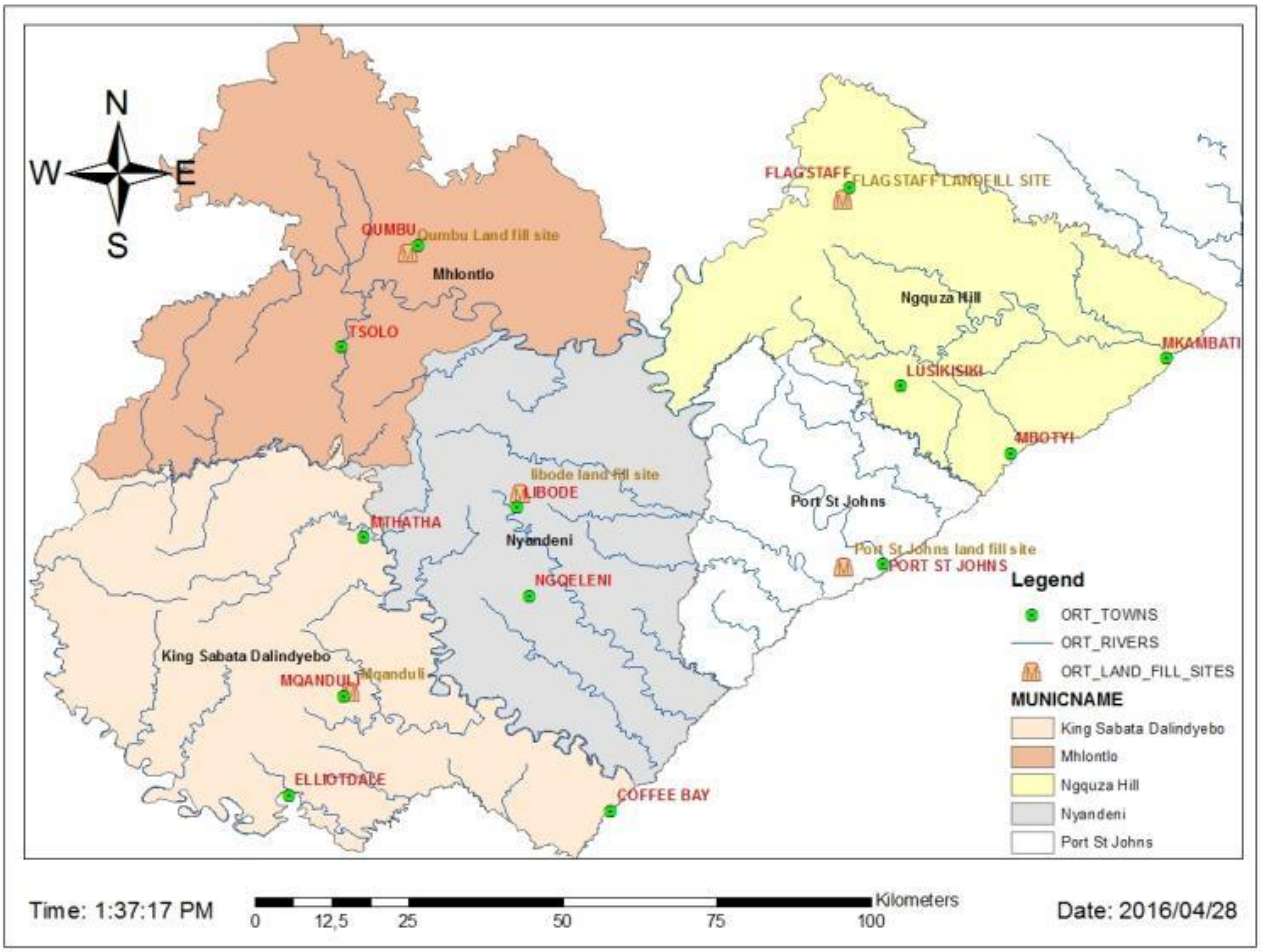

Figure 1. Landfills in the O.R Tambo District Municipality

2.1.3 Age spread and dependency levels

The demographic profile of ORTDM reveals a high dependency ratio, with 41.7% of the population under the age of 15 and only 5.9% over the age of 65 as of 2007. This results in an economically active population of just 52.4%, which is below the Eastern Cape average of 60.5%. While the current high dependency ratio is largely due to the significant youth population, there exists potential for growth in the economically active demographic in the future. If young people remain in the district and acquire necessary skills, they could contribute to local economic development. However, without adequate educational and employment opportunities, many may migrate in search of better prospects [9].

2.1.4 Education

The level of education within a community directly correlates with its overall quality of life. In South Africa, the poverty rate is significantly linked to educational attainment, with 69% of individuals with no formal education living in poverty, compared to only 3% of those with tertiary education. In ORTDM, educational levels are generally low: 24.4% of the population over the age of 15 have never attended school, compared to the provincial average of 14.8%. Only 15% of the population over the age of 15 have completed high school, and a mere 4.3% possess a tertiary education. King Sabata Dalindyebo (KSD), the district's main urban center, accounts for 38% of the district's school leavers and 47% of those with tertiary education. This low level of formal education represents a significant barrier to economic development, as the proportion of residents with a school-leaving certificate or higher falls far below both the provincial and national averages. Furthermore, the out-migration of educated individuals seeking better opportunities exacerbates the socio-economic challenges facing the district [9].

2.1.5 Employment

The unemployment rate in ORTDM is alarmingly high, recorded at 68.1%. However, this figure varies significantly across individual local municipalities. From 1996 to 2007, the district experienced an average annual increase in unemployment of 3.9%. The unemployment rate in KSD is comparatively lower at 52.7%, while Port St. John's faces a staggering rate of 83.6%. This disparity reflects a skewed demographic profile and highlights the trend of economically active individuals migrating from less developed regions to urban centers with better opportunities, particularly Mthatha, which serves as the district's main economic hub. The persistently high unemployment rates underscore the urgent need for targeted initiatives to create jobs and stimulate economic growth in the district [14].

2.1.6 Income levels

Income levels significantly influence the vulnerability and resilience of communities within ORTDM. Approximately 72% of households earn below the poverty line, while 22.4% belong to the middle-income group, and only 5.1% are considered affluent. In 2007, the average annual per capita income in the district was R11,837, significantly lower than the provincial average of R19,945 and the national average of R28,910. Income disparities exist even within the district, with

KSD reporting the highest per capita income at R16,403 per annum. The prevailing low-income levels contribute to the heightened vulnerability of the district's population, making them more susceptible to economic shocks, health crises, and environmental disasters.

2.2 Study population

The O.R. Tambo District Municipality consists of five local municipalities, each of which features an urban service center or town, but the overall district remains predominantly rural. ORTDM is classified as a C2 municipality, indicating that approximately 93% of the population resides in scattered homesteads and small villages. Historically, at least 80% of the district was part of the former Transkei Homeland [9].

The district's diverse landscape, which includes rolling valleys and rugged mountain ranges, plays a crucial role in shaping the socio-economic conditions of its inhabitants. The climatic conditions vary depending on altitude and proximity to the sea, influencing agricultural practices and livelihoods in the area [9].

Four of the five local municipalities within ORTDM Port St. John's, Nyandeni, Ngquza Hill, and Mhlontlo are classified as B4 communities, signifying a rural environment with a predominantly subsistence-based economy. Settlements in these municipalities are generally small and characterized by low-income levels. In contrast, King Sabata Dalindyebo Local Municipality (KSDLM) is classified as a B2 municipality, indicating the presence of a significant urban center with market activities, business opportunities, and relatively productive agricultural land.

King Sabata Dalindyebo is the economic heart of the district. Mthatha, the primary urban center in KSD, not only serves as the economic and administrative hub of the district but also hosts local and district government offices. Mthatha exhibits both urban and rural characteristics, functioning as a key regional economic center. According to 2016 census data, KSD has a total population of 488,349, making it the most populous municipality within ORTDM [14].

Port St. John's is one of the B4 municipalities included in this study. Approximately 90% of Port St. John's residents live in rural areas, with the City of Port St. John's acting as the only true urban center in the region. The municipality, divided into 22 wards, has a total population of 166,778 [9]. Geographically, Port St. John's is located on the Indian Ocean coast, roughly 90 kilometers east of Mthatha, at the mouth of the Umzimvubu River. Covering an area of approximately 1,291 square kilometers, the municipality boasts a robust tourism industry supported by its diverse topography of hills, dunes, rivers, and mountains.

The third municipality analyzed in this study is Mhlontlo, which consists of two urban service centers: Tsolo and Qumbu. Mhlontlo is divided into 29 wards and has a total population of 86,860 [14]. The majority (91.14%) of residents live in rural areas, while 1.68% work on farms, and 7.17% reside in the urban centers. Much of the land in Mhlontlo is communally owned and utilized for agricultural and subsistence purposes, particularly grazing. This predominantly rural environment significantly impacts the socio-economic conditions of the area, shaping the livelihoods and adaptive strategies of local communities.

The populations studied in these municipalities exhibit diverse demographic, economic, and environmental conditions. This diversity provides a comprehensive foundation for understanding how different communities in the O.R. Tambo District are responding to challenges such as climate change and economic development.

2.3 Research design

The study used a qualitative design to investigate the status of leachate management at the landfills. In contrast to quantitative methods that focus on measurable variables, qualitative research delves deeper into social phenomena, such as environmental management practices, and provides a comprehensive insight into the experiences and perspectives of stakeholders [13].

2.4 Data collection methods

The data was collected using two main methods: semi-structured interviews and document analysis.

2.4.1 Semi-structured interviews

In-depth interviews were conducted with key informants directly involved in waste management and landfill operations in the five municipalities of O.R. Tambo District. The interviewees included landfill managers, waste management officials and operational staff. The interview guide contained open-ended questions aimed at obtaining detailed information on current leachate management practices, challenges and possible solutions. All interviews were conducted with informed consent, recorded and transcribed verbatim for further analysis.

2.4.2 Document analysis

A comprehensive review of the relevant literature, including journal articles, reports and government documents, was undertaken. The document analysis also included an examination of the official documents of the O.R. Tambo District Municipality on landfill policies and regulations. The aim of this analysis was to understand the broader context of leachate management in South Africa and to compare local practices with those in developed and developing countries.

2.5 Sampling strategy

A purposive sampling strategy was used to select the landfills for the study. This approach was chosen to identify information-rich cases that best illustrate the phenomenon of interest in this case, effective leachate management [15]. Five authorized landfill sites were selected in the municipalities of Mqanduli, Qumbu, Flagstaff, Port St. John's and Libode. These sites were selected as they are subject to South African leachate management regulations and therefore offer the potential for the assessment of leachate control measures.

2.6 Data analysis

Thematic analysis was used to identify patterns and emergent themes in the data. An explicitly phenomenological approach was adopted to capture participants lived experiences of leachate management [16]. Interview transcripts were reviewed line by line, coded to reflect participants' insights and categorized into key themes. The document analysis followed a similar process and focused on landfill practices and relevant national or regional regulations. The analysis also explored four levels of collaborative

governance, supported by empirical data, to gain a comprehensive understanding of stakeholder interactions and decision-making in leachate management.

2.7 Justification for qualitative approach

A qualitative approach was chosen as it can capture the complex social, regulatory and environmental dynamics influencing leachate management practices. The interviews allowed for an exploration of the personal experiences and challenges faced by landfill operators and provided insights that would have been impossible to capture with quantitative data alone. The document analysis provided a broader context by demonstrating how national policy and local regulations impact landfill operations, allowing for a comprehensive understanding of current leachate management practices.

3. RESULTS

This section presents the results of the study on landfill leachate management in the five municipalities of the OR Tambo District Municipality (ORTDM), South Africa. The data was collected through semi-structured interviews with landfill managers and waste management officials, field observations and document analysis. To increase the credibility of the data, validation measures such as cross-checking of respondents and expert review were used.

The results indicate significant deficiencies in leachate management infrastructure in all municipalities, with open dumping still prevalent in three areas. Table 1 is used to summarize these landfill conditions. Past cases of leachate contamination have been documented in ORTDM, including groundwater contamination from unlined landfills. In addition, consumer habits have changed, affecting the composition of waste and necessitating adaptation of leachate management strategies. Financial constraints were identified as one of the main barriers to the implementation of effective leachate collection and treatment systems. In addition, regulatory inconsistencies between policy and practice were identified when reviewing the documents, highlighting the challenges in enforcing waste management have significant deficiencies.

Table 1. Summary of landfill conditions

Municipality	Leachate Collection System	Waste Cells	Waste Compaction	Drainage System	Security Measures	Financial Constraints	Compliance Level	Historio Contan
KSD	Partial (Basin, no sump)	3 cells	Inconsistent	None	Fencing, signage	High (No dewatering system)	Moderate	Yes
Nyandeni	Partial (Basin, no sump)	4 cells	Poor (Lack of soil cover)	None	Fencing (but livestock access)	High	Low	Yes
Ngqu a Hill	None	Open dumping	None	None	No fencing or signage	Very High	Very Low	Yes
Mhlontlo	Partial (Basin, poor drainage)	Limited	Sporadic	None	Fencing, signage	High	Moderate	Yes
Port St. Joln's	None	Open dumping	None	None	No fencing	Very High	Very Low	Yes

3.1 Local municipality findings

The study found that leachate management practices in the five municipalities are generally inadequate, with significant deficiencies in infrastructure, operational management and regulatory compliance. The following subsections provide a detailed analysis of leachate management in each municipality, highlighting the key challenges and their impact on the environment.

a) King Sabata Dalindyebo (KSD) local municipality

The Mqanduli landfill in KSD consists of three functioning waste cells and a leachate collection basin. However, the lack of a functioning leachate collection system remains a critical problem. Despite historical records of groundwater contamination associated with leachate seepage, no remedial action has been taken. Compaction of the waste is sporadic due to financial constraints and there is a lack of essential equipment such as a compactor lorry and a dewatering system. Although the landfill has simple fencing and signage, the overall leachate management is inadequate and poses a significant environmental risk.

b) Nyandeni local municipality

At the Qumbu landfill in Nyandeni, there are four operational waste cells and a leachate collection basin, but there is no leachate sump, which prevents efficient leachate management. Similar to KSD, this landfill lacks proper soil cover and waste compaction, which raises significant concerns about long-term waste stabilization and leachate prevention. Although the landfill is fenced, there is no signage at the entrance and security personnel are primarily concerned with preventing livestock from entering the landfill rather than monitoring the type and quantity of waste deposited. This indicates a need for better operational oversight and more effective waste monitoring.

c) Ngquza Hill local municipality

The Ngquza Hill landfill is an authorized open dumpsite but lacks basic landfill management elements such as designated waste disposal cells, a soil cover, a leachate collection system and a reservoir. Open dumping is widespread and increases the risk of leachate entering the surrounding ecosystems. Fires have been observed at the landfill, further increasing the

environmental and health risks. The landfill is neither fenced nor signposted, so people and animals have unrestricted access. Theft of fencing material and ongoing budgetary constraints were cited as major challenges to improving landfill conditions.

d) Mhlontlo local municipality

The Mhlontlo landfill is similar to the Mqanduli landfill in KSD. Although the landfill is fenced and has signs indicating the types of waste allowed, the leachate collection basin lacks an effective drainage system. Historical records show that leachate has repeatedly overflowed into nearby water sources without formal remedial action being taken. The site lacks adequate infrastructure for sustainable leachate management, indicating systemic problems with landfill operations throughout ORTDM.

e) Port St. John's local municipality

The Port St John's landfill harbours the greatest environmental risks of the sites investigated. It has no structured leachate management system and no infrastructure for the collection or treatment of leachate. Although it is a licenced facility, the operating standards are far below regulatory requirements, effectively functioning as an unmanaged landfill. The proximity of the landfill to local communities and water sources increases the risk of leachate contamination, which has been documented in previous community reports. As leachate control guidelines are not enforced, regulatory inconsistencies are evident.

3.2 Summary of leachate management practices observed

In all five municipalities, the study identified significant deficiencies in the landfill infrastructure and leachate disposal. The following key issues were identified:

- Inadequate leachate collection systems: Most landfills, including those in KSD, Nyandeni, Mhlontlo and Port St John's, do not have functional leachate collection and treatment systems, which increases the risk of groundwater contamination.
- Poor waste compaction and land cover: Compaction practices are inconsistent due to budget constraints. In Nyandeni, for example, the landfill is not properly covered, allowing rainwater to penetrate and increasing leachate formation.
- Lack of drainage systems: Even where there are leachate collection basins, such as in KSD and Mhlontlo, the lack of drainage systems prevents effective leachate collection and disposal.
- Inconsistencies in the regulations: Discrepancies between waste management policies and actual practices at the landfills were found when analyzing the documents. Gaps in the enforcement of regulations were particularly evident at landfills operating as open dumps.
- Financial constraints: Budgetary constraints were repeatedly cited as an obstacle to effective leachate management. The lack of equipment, including compactors and dewatering systems, prevents municipalities from implementing sustainable landfill operations.
- Impact of changing consumer habits on waste composition: Changing consumer habits have altered waste streams and require more adaptable leachate management strategies to cope with increasing volumes of plastic and electronic waste.
- Historical incidents of leachate contamination: Municipal records document past cases of groundwater contamination associated with landfill leachate seepage and highlight the environmental consequences of inadequate landfill management.

3.3 Overall findings

The results of this study show that leachate management practices in ORTDM urgently need to be improved. None of the five municipalities analyzed have adequate leachate collection or treatment systems. In at least three municipalities, open dumping of leachate is still widespread, increasing the risk of environmental pollution. Documented incidents of leachate contamination in the past emphasize the long-term effects of poor landfill management, particularly regarding groundwater quality.

Regulatory inconsistencies between national waste management policy and actual landfill operations further complicate efforts to improve leachate control. Many facilities do not adhere to the prescribed landfill regulations and enforcement remains weak. In addition, financial constraints limit the ability of municipalities to invest in key landfill infrastructure.

To address these challenges, this study highlights the potential role of public-private partnerships (PPPs) in financing and implementing sustainable solutions for leachate management. An assessment of the feasibility of PPPs suggests that working with private waste management companies could help close infrastructure gaps, introduce best practices and improve the overall management of landfills.

4. DISCUSSION

This section examines the key findings of the study, focusing on the challenges associated with leachate management in the O.R. Tambo District Municipality (ORTDM) and suggests possible solutions. The study highlights critical infrastructure deficiencies, policy and regulatory gaps and the urgent need for comprehensive strategies to mitigate the environmental risks posed by ineffective leachate management.

4.1 Critical infrastructure deficiencies and environmental impacts

The study shows that most landfills in ORTDM do not have adequate infrastructure for leachate management. Essential components such as leachate collection systems, retention basins and effective landfill liners are either non-existent or poorly implemented [2]. The King Sabata Dalindyebo (KSD) landfill is an example of these shortcomings. Although it has a leachate collection basin, it does not have a functional sealing system. Budget constraints have further hindered the purchase of key equipment such as compactors and dewatering systems, resulting in inconsistent waste compaction and inadequate management practices.

In addition, poor disposal practices were observed at several landfill sites, particularly the open dumps at Ngquza Hill and Port St John's. As there are no designated disposal cells at these sites, the uncompacted waste is exposed to environmental elements, which significantly increases the risk

of leachate formation. Rainwater infiltration into the waste piles not only accelerates leachate formation but also increases the likelihood of soil and groundwater contamination [17]. Poor landfill infrastructure exacerbates the accumulation of these contaminants and leads to long-term ecological damage and health crises [18]. The lack of designated cells and effective capping systems at the Ngquza Hill, Libode and Mhlohlo landfills makes them highly susceptible to rainwater infiltration and leachate pollution.

The inadequate management of leachate poses a serious threat to human health and the surrounding ecosystems. Leachate, which contains a complex mixture of pollutants, can seep through the soil and contaminate groundwater sources [2]. The consumption or use of contaminated water can lead to serious health problems for the local population [19]. In addition, the uncontrolled release of leachate can disrupt ecosystems by introducing hazardous substances and ultimately affect biodiversity and the ecological balance [20]. A similar situation in Nigeria, where the lack of standardized treatment techniques due to leachate intrusion has led to persistent outbreaks of cholera and malaria, underlines the urgency to address these shortcomings [21].

4.2 Policy and regulatory gaps

The results indicate significant policy and regulatory shortcomings in landfill management in ORTDM. Observations from solid waste managers indicate that environmental impact assessments (EIAs) are not conducted prior to landfill site selection, revealing critical deficiencies in policy implementation. As Ntsele et al. [22] emphasis, effective waste management in South Africa requires a sound environmental policy and legislative framework. The lack of such a framework contributes to the observed shortcomings in the planning and operation of landfills.

Interestingly, all the landfills studied had an operating license, which raises concerns about enforcement. The Environmental Protection Act (Act No. 73 of 1989) sets minimum standards for the licensing of landfills, including leachate management requirements (Department of Water Affairs & Forestry, 1998). However, the discrepancy between legal requirements and actual conditions at landfill sites suggests weak enforcement mechanisms [23]. This emphasis the need for stricter oversight to ensure compliance with established standards.

4.3 A multi-pronged approach for sustainable leachate management

Overcoming these challenges requires a comprehensive, multi-faceted approach to achieve sustainable leachate management in ORTDM. Increased funding and infrastructure development are critical to implementing effective leachate control systems. Investment in designated waste management cells, leachate collection systems and daily cover practices are essential [24]. Securing additional funding through alternative mechanisms, such as public-private partnerships, could provide the necessary resources for infrastructure improvements. Improving design and operational standards for landfills is also critical. Implementing best practices, such as designated waste disposal cells and efficient leachate collection systems, can significantly reduce the generation of leachate and its impact on the environment. The introduction of clear regulations for the design and operation of landfill sites will ensure compliance with best practice.

Strengthening the waste management policy and legal framework is equally important. The development of a comprehensive environmental policy that requires environmental impact assessments for the siting and operation of landfills will promote compliance with best practices [25]. In addition, enforcing stricter compliance through regular inspections and penalties for non-compliance can incentivize landfill operators to adhere to legal standards [23].

Investment in capacity building and community involvement can further improve leachate management. Training programs for waste management staff improve their technical competence, while public awareness campaigns can educate residents about the risks of leachate and the importance of responsible waste management. Community involvement fosters a sense of ownership and encourages greater participation in local waste management initiatives [26].

4.4 Technological progress and sustainable practices

The integration of advanced leachate treatment technologies and sustainable waste management practices can further enhance leachate control efforts in ORTDM. Innovative treatment technologies offer promising solutions to improve leachate quality and reduce environmental risks. Techniques such as membrane filtration, advanced oxidation processes, and biological treatment methods effectively remove contaminants and make leachate safer for disposal or potential reuse in certain applications [10, 11]. Assessing the feasibility of these technologies and integrating them into existing landfill operations can lead to significant improvements.

Waste segregation can also reduce both leachate volume and contaminant loading. Encouraging residents to separate recyclables and organic waste will reduce the flow of harmful materials into landfills. In addition, the installation of bioreactors in landfills can accelerate the biodegradation of organic waste, minimize the formation of leachate and improve its composition [12]. These bioreactors create optimal conditions for microbial activity and thus improve the sustainability of landfill operations.

4.5 Collaboration and public-private partnerships

Effective leachate management in the context of ORTDM requires the cooperation of various stakeholders, including government agencies, municipalities, private sector organizations and civil society [27]. Government authorities at national and regional level play a central role in environmental protection and waste management. Greater coordination between different levels of government can improve the enforcement of regulations and the allocation of resources [28].

Local municipalities responsible for waste collection and landfill management can benefit from partnerships with private sector experts. Private companies specializing in landfill design and leachate treatment technologies can provide important expertise and financial support [29]. Public-private partnerships (PPPs) offer the opportunity to co-finance and manage landfill operations to ensure sustainable practices [30]. Civil society organizations (CSOs), including non-governmental organizations (NGOs) and community groups, contribute by raising awareness of the risks associated with leachate. These organizations can facilitate public

participation in waste management and hold authorities accountable for environmental sustainability [31]. Community engagement through education and information initiatives promotes a sense of ownership of waste management and leads to better environmental outcomes [32].

4.6 Environmental risks and impacts

The study emphasizes the considerable deficits in leachate management at ORTDM landfills. The lack of essential landfill components, including proper siting, construction practices, liners and leachate collection systems, poses a high risk of leachate migration and subsequent contamination of surrounding soils and groundwater sources [17]. Waste managers have identified inadequate budget allocations as a major obstacle to the selection of suitable sites and the implementation of key design features [33]. To overcome these challenges, prioritizing budget allocation for waste management infrastructure, enforcing appropriate design standards and employing qualified staff are important steps towards sustainable leachate management in ORTDM.

5. RECOMMENDATIONS

A multi-pronged approach is needed to improve leachate management at landfills in the O.R. Tambo District Municipality. The following recommendations are proposed:

5.1 Increased budget allocation and infrastructure investment

Providing more funding for leachate control infrastructure, including designated waste cells, leachate collection systems, landfill liners and daily capping systems, is critical [24]. Exploring alternative funding mechanisms, such as public-private partnerships, could help alleviate budget constraints. In addition, sustained investment in technological advances such as membrane filtration and advanced oxidation processes can improve the efficiency of leachate treatment.

5.2 Improved landfill design and operations

The application of appropriate landfill design principles is essential to prevent the formation and migration of leachate. These include designated cells, effective leachate collection systems, landfill liners and daily capping systems to control infiltration of rainwater and reduce leachate generation [24]. Advanced treatment technologies should also be integrated into landfill operations to improve environmental outcomes.

5.3 Comprehensive policy and legislative framework

A clearly defined environmental policy and a legal framework for waste management are necessary. The framework should require environmental impact assessments (EIAs) for the siting and operation of landfills and ensure compliance with best practice [25]. Strengthening enforcement mechanisms through regular inspections and penalties will further incentivize compliance with landfill management standards [23].

5.4 Capacity building and culturally relevant public awareness

Investment in capacity building programs for waste management staff is crucial to improve their knowledge and skills in landfill operations, especially in leachate control. In addition, public awareness campaigns should take cultural factors to encourage community participation in responsible waste management and environmental protection.

5.5 Sustainable public-private partnerships (PPPs)

Ensuring long-term economic viability through well-structured PPPs is crucial. Contract structuring should include risk mitigation strategies to encourage private sector involvement while safeguarding the public interest and environmental sustainability.

By implementing these recommendations, the O.R. Tambo District Municipality can move towards more sustainable and environmentally sound landfill management.

6. CONCLUSION

This study has identified critical deficiencies in leachate management at the landfills in the O.R. Tambo District Municipality. The lack of essential infrastructure such as landfill liners, leachate containment systems and appropriate cover materials poses a significant risk to the environment and public health. These problems are exacerbated by inadequate funding, which hinders the development of adequate landfill infrastructure, the selection of suitable sites and the recruitment of qualified personnel.

The findings emphasis the urgent need for a multi-faceted approach to improve landfill management. Increased funding for waste management is essential to implement the principles of proper landfill design, including the use of designated waste cells, leachate collection systems and daily capping practices. Strengthening environmental policy and ensuring that environmental impact assessments (EIAs) are carried out for landfill operations will help to enforce best practice.

In addition, robust enforcement mechanisms such as regular inspections and penalties for non-compliance are necessary to ensure that landfill operators adhere to regulations. Investment in capacity building programs for waste management staff will improve their skills in dealing with landfills and leachate, while public awareness campaigns will promote community understanding of the importance of responsible waste management.

By adopting these recommendations, the O.R. Tambo District Municipality can introduce more sustainable landfill management practices that protect both public health and the environment.

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