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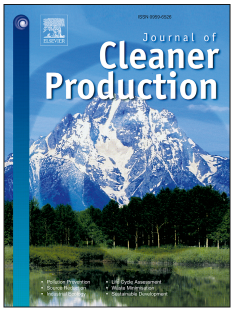

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Deterioration modes, mechanisms, and effects of flexible landfill facilities disposing hazardous waste

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Abstract: Dynamic performance and lifespan predictions are essential for understanding the whole life-cycle emissions and environmental impacts of landfills. However, there are knowledge gaps regarding the major failure modes and mechanisms in flexible hazardous waste landfills (FHWLs) and their potential effects on the service life of landfills. These issues limit the advancement of related research. In this study, focusing on flexible landfills, failure mode, mechanism, and effects analysis was conducted to identify the major failure modes, mechanisms, and impacts that may occur in landfills under extremely harsh chemical and stress conditions. The results indicate that there are approximately 33 major components and materials in landfills, corresponding to 35 potential failure modes and more than 60 underlying failure mechanisms. Notably, the failure of the drainage media in the drainage system is concerning and challenging to recover from. In contrast, the failure of the high-density polyethylene geomembrane (HDPE GMB) in the liner system (LS) is considered serious and is prone to occur, but it is also difficult to detect. Therefore, these two failure modes were identified as critical factors affecting the degradation of the performance and longevity of FHWLs. Finally, due to their high probability of occurrence and severe impacts, stress damage (physical damage) and oxidative aging were identified as the main degradation modes of HDPE GMB, the core material in FHWLs. This study provides key insights into performance prediction targets, failure modes, and failure mechanisms for further research on long-term landfill performance and life prediction. It prompts the government and stakeholders to re-examine the rationality behind the positioning of landfills, such as the assumptions of unlimited service and solid waste management endpoints. Therefore, it calls for a reassessment and optimization of the full life cycle emissions of landfills and related waste.

Keywords: Landfill, Material aging, Long-term performance, service life

1. Introduction

Landfills are the environmental infrastructure for the centralized disposal of large quantities of solid waste (Gunarathne et al., 2024). Landfill failure can lead to environmental contamination and ecological damage from the leakage of hazardous substances (Nguyen et al., 2021). Engineered materials in landfills undergo degradation under complex pressure, hydrological and biogeochemical conditions (Narani et al., 2020). Interactions such as holes in the artificial liner, or increased hydraulic loads due to increased leachate generation or reduced conductivity, result in exponential increases in leakage (Parameswari et al., 2021, He et al., 2019). Failure occurs when leakage reaches an unacceptable level. Wastes, as well as secondary high-level leachate, may contain many contaminants, including, but not limited to, heavy metals, high nitrogen content (primarily as ammonia) and emerging contaminants. (Xu et al., 2018, Wang et al., 2022). Considering that a cumulative total of 100 billion tons of solid waste has been deposited in 10,000 landfills worldwide, some of which have been in service for more than 20 years, the probability of failure and the potentially catastrophic environmental consequences on a global scale need to be taken seriously (Mahadi H M et al., 2023).

This highlights the importance of failure analysis of landfills. Failure modes, mechanisms, and consequences, if accurately identified, can help in taking targeted measures to slow down failure as well as in accurately predicting failure and taking countermeasures in advance (Garavaglia et al., 2019, Verbist et al., 2019). Early studies focused on indirectly determining failure by monitoring groundwater contamination in the vicinity of the landfill. As the evidence of failure became more conclusive, more attention was paid to the study of failure itself. At this stage, accelerated aging simulation experiments were conducted to study the performance degradation patterns and influencing factors of key core materials. For example, Fady et al. (2014) studied the aging characteristics of a high-density polyethylene geomembrane (HDPE GMB), a type of flexible membrane liner, in landfills; Yu et al. (2020) studied changes in geotextile performance over time; and Wang et al. (2021) studied changes in the permeability coefficient of the guiding and drainage layer. During landfill operation, the performance of the guiding drainage system and the liner system (LS) will gradually decline (Singh et al., 2009). Studies on impervious geotechnical materials have shown that, due to temperature changes, ultraviolet radiation, and chemical corrosion, the impervious performance of an HDPE GMB will gradually decline, and the number of holes in the material will gradually increase (Abdelaal et al., 2014).

However, landfills are complex systems, and failures of different components can compound and affect each other, resulting in more serious consequences (Nai et al., 2021). Previous studies have focused on the failure of a single component and have failed to systematically identify what specific components and functions landfills have, and what failure modes and consequences exist for these components. Consequently, it is also difficult to help systematically understand how the landfill, as a whole, will fail, how likely it is, and what the consequences will be. The U.S. EPA has explored some of the possible long-term degradation, but it is not comprehensive and does not analyze in depth the mechanisms behind these degradations (Cortellazzo et al., 2022), as well as the possible consequences and their likelihood, severity, detectability, and reparability, which has severely limited the development of further research on landfill life prediction and extended service life.

In this study, a flexible hazardous waste landfill (FHWL), which disposes of hazardous waste and employs a flexible pollution barrier structure and thus poses a greater risk, was selected for conducting failure modes, mechanisms, and effects analysis (FMMEA). By analyzing the structure and composition of the FHWL in conjunction with its service environment and stress conditions, the long-term performance degradation of key components and materials was identified. Further analysis was conducted in terms of the failure impact, severity, frequency, and detectability of each component to determine the key components and materials affecting the lifetime of the FHWL, as well as their failure mechanisms. This research is important for quantitatively predicting landfill failure and service life and for designing and optimizing the service environment to mitigate performance degradation and extend the service life of landfills.

2. Materials and methods

2.1 FHWL system composition and function identification

To conduct FMMEA, the system composition, boundary, and main functions of landfills were first analyzed and identified.

2.1.1 FHWL system composition

In a broad sense, a FHWL is a land-based disposal facility for the disposal of hazardous wastes. FHWLs are composed of several functional units and structures, mainly including the receiving and storage facilities, analysis and identification systems, pretreatment facilities, landfill disposal facilities (including the LS, leachate collection and drainage system, and closure and coverage system), leachate and wastewater treatment system, environmental monitoring system, emergency facilities, and other public works and supporting facilities (Li et al., 2012). In the narrow sense, A FHWL refers to the landfill disposal facilities mentioned earlier; this narrow sense of a FHWL is the specific research subject of this article.

Many countries have stipulated minimum design requirements for FHWLs (Xu et al., 2023). The basic components of a FHWL include the groundwater drainage subsystem, the rainwater and sewage diversion (RSD) subsystem, the flood interception ditch, the leachate seepage prevention subsystem, the leachate drainage subsystem, and the site closure and coverage subsystem. Some valley landfills may also be equipped with dams. Landfills with high regional groundwater levels are also equipped with groundwater drainage and collection subsystems.

Notably, according to the differences in engineering barrier structures, FHWLs are divided into flexible landfills and rigid landfills (Xu et al., 2023). Flexible landfills refer to landfill disposal facilities that use double artificial composite liners as engineering barrier materials; rigid landfills are landfill disposal facilities that use concrete as engineering barrier materials (Wai Ng et al., 2023). This study focuses on FHWLs; therefore, unless otherwise specified, the term "landfill" in the following sections refers to a FHWL.

The structure of the FHWL system is shown in Figure 1, and the components or materials of each subsystem are shown in Table 1 (Xu et al., 2018).

Table 1 Codes, names, and components of the structural subsystems of the FHWL

Subsystem code	Subsystem name	Components
RSD	Rain and sewage diversion	Drainage ditch
CG	Capping green system	Vegetative soil, covering supporting soil, and plants
CCD	Capping water collection and drainage system	Drainage medium and slope drainage net
CL	Capping liner system	HDPE GMB
CGC	Capping gas collection system	Drainage medium and drainage pipe

WL	Waste landfill body	Hazardous waste
PLC	Primary leachate collection and drainage system	Filter layer, drainage medium, and leachate drainage pipe
PL	Primary liner system	HDPE GMB, geotextile protective layer, and clay liner
SLC	Secondary leachate collection and drainage system	Drainage net and drainage pipe
SL	Secondary liner system	HDPE GMB, geotextile protective layer, and clay liner
GCD	Groundwater collection and drainage system	Drainage medium and drainage pipe

Note: FHWL = Flexible hazardous waste landfill; HDPE GMB = High-density polyethylene geomembrane.

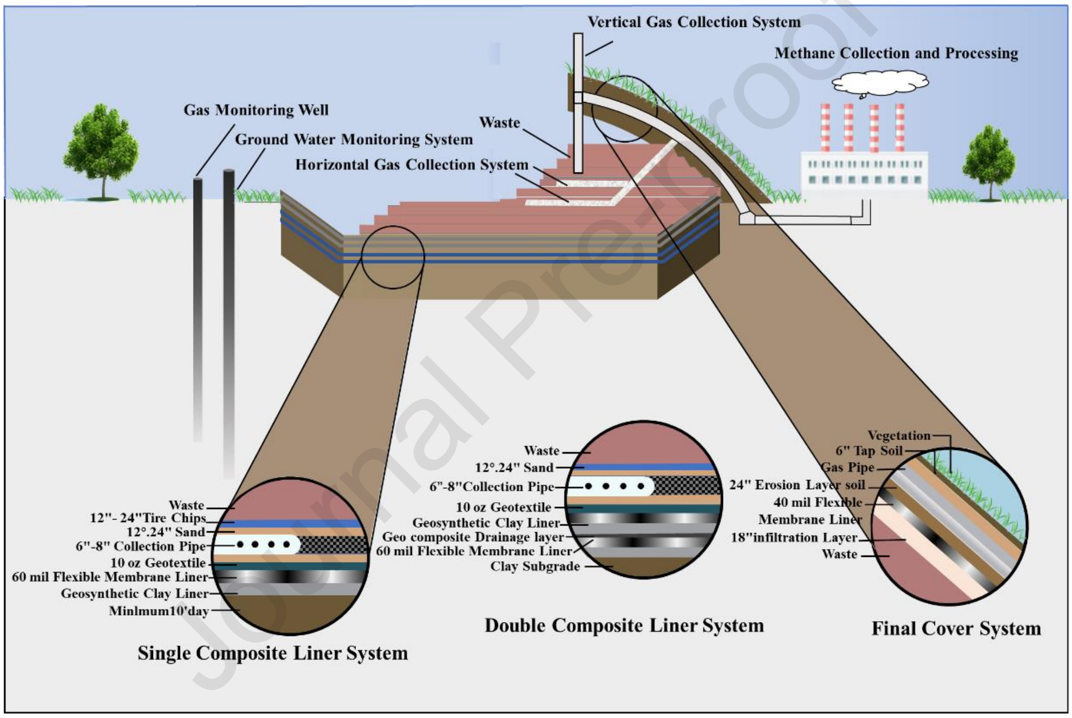

Figure 1 Typical flexible hazardous waste landfill (FHWL) system structure.

2.1.2 FHWL function and its implementation

A FHWL achieves safe disposal by isolating hazardous waste from the external soil, surface, and groundwater environment. The leachate leakage control in a FHWL is achieved through the triple control of the source, routine, and sink. Source control refers to controlling the infiltration of rainwater and the production of leachate. This is mainly achieved through RSD and capping water collection and drainage (CCD), both of which make use of the drainage function; in contrast, the LS exercises the barrier function of the landfill. Route control refers to the cutoff of leachate leakage routes—mainly through the barrier function of the main leachate LS and the drainage function of the drainage system. The function of route control is to avoid or minimize the leachate leakage through the main liner layer under the unfavorable conditions of massive leachate generation. Sink control refers to the collection of leachate leakage through the main liner layer by setting up a secondary leachate LS and drainage system. The secondary leachate LS is the final barrier for FHWL leachate leakage. Along with the main LS, the secondary system constitutes a form of "double insurance." This is to ensure that even if the main liner layer leaks, the leachate will not enter the environmental media. The functional characteristics and water flow characteristics of each FHWL subsystem are shown in Figure 2.

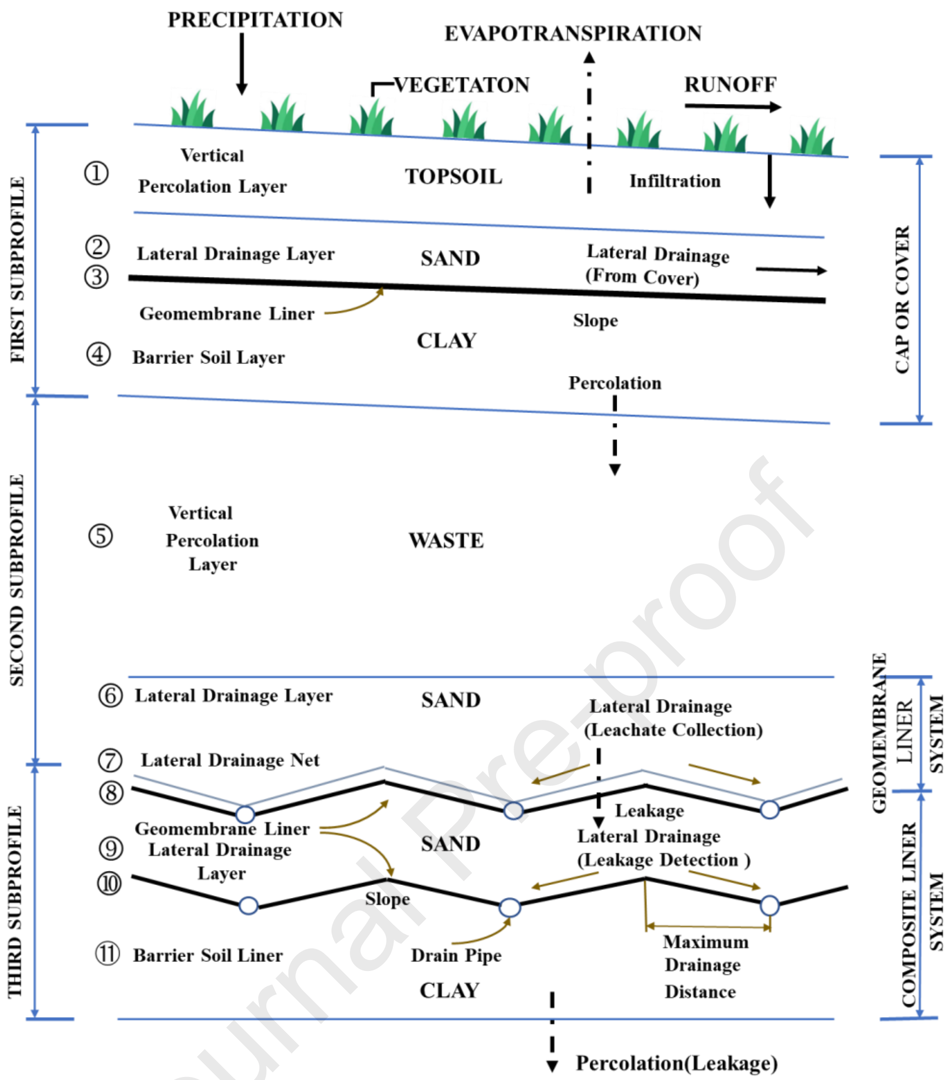

Figure 2 Functional characteristics and water flow characteristics of flexible hazardous waste landfill (FHWL) subsystems. Revised according to Berger (2015).

2.2 FMMEA methods

FMMEA is "a systematic methodology to identify potential failure mechanisms and models for all potential failure modes, and to prioritize failure mechanisms" (Christopher et al., 2015). It is the cornerstone of the physics-of-failure approach to the reliability assessment of systems, subsystems, and components.

FMMEA is derived from the well-established failure mode and effects analysis

(FMEA) method, which was developed to identify and classify failures with a focus on mission success and safety. However, in contrast to traditional FMEA, FMMEA considers failure mechanisms and their relevance when assessing potential system risks. The implementation of FMMEA includes failure mode identification, failure mechanism analysis, and failure consequence analysis. The FMMEA process is described in detail in Blancke et al. (2018).

Prior to conducting the FMMEA, the landfill component or material to be analyzed was identified in accordance with Section 2.1. After that, the location of the landfill component or material in the FHWL system was analyzed in terms of the surrounding parts that it systematically interferes with. Factors within and outside the system affecting the landfill location were also analyzed. FMMEA was then conducted, with the first step being failure mode identification using a combination of theoretical analyses and empirical studies. The empirical studies were mainly based on using reported literature or other information to analyze failure modes. To identify possible degradation modes, the theoretical analyses were based on the physicochemical properties of the material itself. Moreover, the theoretical analyses take into account the physicochemical conditions and physicochemical processes the material may undergo during its service life. For example, according to the poor puncture performance of HDPE GMB, the "puncture" failure mode can be identified by analyzing the forces it may encounter during its service life.

The second step, failure mechanism analysis, focused on the identified failure modes and determined the physicochemical processes and mechanisms underlying the failure modes through theoretical analysis. For example, for the drainage medium failure mode of "clogging," it was possible to infer the existence of three possible failure mechanisms: the chemical precipitation of calcium and magnesium ions in leachate, the physical sedimentation or accumulation of particulate matter, and the biodegradation and synthesis of organic matter. Among these, the biodegradation and synthesis of organic matter release nutrients that promote favorable conditions for microbial growth, thereby facilitating the formation of biofilm/microbial communities, ultimately leading to partial or complete blockage of the pipeline or system (Tang et al., 2018). Understanding the physical and chemical composition of the leachate is crucial for comprehending all these mechanisms and their interconnectedness.

Finally, the possible effects of the failure mode were analyzed. For example, in terms of drainage medium clogging, it was inferred that at the level of the leakage detection and collection system (LDCS), clogging would lead to the failure of leachate collection and drainage, resulting in an increase in the water level. At the level of the FHWL system, this would lead to an increase in the water pressure exerted on the LS, and an increase in the amount and groundwater contamination risk of leakage. Detailed information about FMMEA is provided in Blancke et al. (2018).

3. Results

3.1 Factors, modes, and mechanisms of FHWL deterioration

According to the definition and structural composition of the FHWL system, failure modes were identified for each underlying system with respect to the function of each component, its material properties, the service environmental conditions, and the stress conditions. According to the material characteristics, environment, and leachate conditions in FHWL, the degradation and failure mechanism of each failure mode were analyzed. Table 2 shows the results.

As shown in Table 2, a total of 33 degradation factors were identified, corresponding to 35 potential failure modes and 62 potential deterioration mechanisms (Ya, X et al., 2023). According to Table 2, the RSD, CG, RD, RLS, GDS, LD, PL, LDCS, SL, and GCD subsystems were found to have 2, 4, 1, 3, 3, 8, 3, 5, 3 and 3 failure modes, respectively. Of these, in terms of the failure mechanisms suffered, the RD、LD and LDCS systems include biological, physical, and chemical clogging. Biological clogging is caused by microbial activity, where growth and metabolism promote the formation of biofilms and other organic blockages, significantly reducing system permeability due to the production of extracellular polymeric substances (Tang et al., 2018; Wang et al., 2023). Physical clogging occurs when soil particles and garbage residues are carried by water flow and accumulate in the filtration medium or pipes, reducing water flow channels and affecting drainage efficiency (Liu et al., 2021). Chemical clogging happens when inorganic and organic compounds in the leachate react under specific conditions to form precipitates or solids, not only obstructing the drainage system but also potentially corroding system materials with newly formed substances (Wu et al., 2018; Wang et al., 2023). In the RLS, PL, and SL systems, the stress damage of HDPE membranes is attributed to mechanical forces, stones, and tree roots during laying and garbage landfill processes (Ya, X et al., 2023). Meanwhile, the oxidative aging of these systems is caused by the reaction between oxidants in air and leachate with the polymers in the HDPE membrane. The clay in various impermeabilization systems and the soil in the site greening system can suffer structural damage due to particle loss from high-speed water erosion (Li et al., 2021).

Failure studies have been carried out on various landfill subsystems, and research related to subsystems, such as the cover system (Buckley et al., 2012; Dassanayake et al., 2022), LS (Shi et al., 2012; Kerry Rowe et al., 2023), and leachate drainage system (Liu et al., 2020; Wang et al., 2023), has attracted the most attention. Using the relevant failure modes as keywords, such as "landfill cover system failure," "landfill drainage system failure," and "landfill barrier system failure," 8795, 5818, and 3065 relevant scientific papers were retrieved, respectively, from the ScienceDirect database. The findings of these studies indicate that the failure of cover systems mainly leads to the failure of landfill gas collection functions, especially the methane control function of municipal solid waste landfills (Wen et al., 2023). The failure of LSs is mainly due to mechanical breakage or aging (Wan et al., 2023), and the failure of conduit drainage systems occurs due to the siltation of the conduit drainage medium and pipeline ruptures (Xu et al., 2022). Given the low organic content of hazardous wastes, methane escape due to the failure of the cover system may not be of particular concern (Hanson, J.L et al., 2023; Maciel, F.J et al., 2011); however, the failure of the liner and conductor systems may need to be prioritized due to the risk of the release of highly toxic leachate (Xu et al., 2018; Kerry Rowe et al., 2023).

Table 2 Identification of failure modes and failure mechanisms (degradation factors) of landfill subsystems and components/materials

Subsystem	Subsystem/component	Material	Function	Failure mode	Number	Service environmental factors	Service stress conditions	Deterioration mechanism
RSD (Beaven et al., 2013)	Drainage	Ditch concrete	Collect and discharge rainwater and control the water volume in the landfill	1. Drainage ditch blockage occurs 2. Drainage ditch body is broken	2	Rain, light, and temperature		Dry–wet cycle, acid–base corrosion, and stress damage
CG (Chen et al., 2023)	Surface vegetation soil	Soil	Provide nutrition for vegetation	Erosion and loss		Rain, plant roots, and small animals		Rainwater scouring and biological action
	Covering support soil	Soil	Provide support for vegetated soil	-	4	Plant roots and small animals		Biological action
	Vegetation	Grass\trees	Greening/beautification	Decay, death		Rain wash, temperature, and light		Nutrition, dry/wet conditions
RD (VanGulck, et al., 2004)	Drainage medium Geo-drainage mesh	Pebble/gravel/geo-drainage mesh	Guide and drain rainwater to prevent HDPE GMB from accumulating rainwater	Blockage	1	rain		CBPC
RLS (Wan et al., 2023)	HDPE GMB	HDPE GMB	Rainproof and control of leachate	1. HDPE GMB is damaged, and leaks occur		Rain, temperature	USO	Mechanical damage and OA
	Geotextile protective layer	Geotextile	Protect HDPE GMB from damage	2. Permeability coefficient increases Mechanical performance degrades	3	Rain, temperature	USO	SD and OA
GDS (Nelson et al., 2022)	Gas collection and drainage pipe	HDPE pipe	Landfill gas collection and drainage to avoid gas accumulation in the site	1. Cracking 2. Clogging	3	Landfill gas and leachate	DSPB	SD and OA
	Landfill	Hazardous waste	/	Degradation of curing performance		Rainwater, temperature, and leachate	DSPB	/
LD (Rowe et al., 2008)	Filter layer	Fine sand/geotextile	Slow down the clogging of guide and drainage medium	Mechanical performance degradation		Leachate	Ll	SD and OA
	Drainage medium	Pebble/gravel	Conduct drainage and prevent leachate accumulation	Clogging		Leachate	Ll	CBPS
	Central spine drain	HDPE pipe	Collect the leachate in the drainage branch pipe and drainage medium	1. Cracking 2. Clogging	8	L&T	LlUS	CL, SD, and OA
	Spur drain	HDPE pipe	Collect the leachate in the drainage medium	1. Cracking 2. Clogging		L&T	LlUS	CL, SD, and OA
	Guide standpipe	HDPE pipe	Collect the leachate from the main drainage pipe	Cracking		L&T	LlUS	CL, SD, and OA
	Water pump	Water pump	Discharge the leachate from the vertical pipe	Cannot pump water		L&T	/	Corrosion and OA
PL	Flexible membrane liner	HDPE GMB	The first liner barrier for leachate leakage	1. HDPE GMB is damaged, and leaks occur		L&T	LlUS	SD and OA

Subsystem	Subsystem/component	Material	Function	Failure mode	Number	Service environmental factors	Service stress conditions	Deterioration mechanism
(Rowe et al., 2009; Sun et al., 2019)				2. Permeability coefficient increases				
	Geotextile protective layer	Geotextile	Prevent HDPE GMB damage	Mechanical performance degrades	3	L&T	LlUS	SD and OA
	Clay liner	Clay	Together with the HDPE GMB, it forms the first liner barrier	Permeability coefficient increases		L&T	LlUS	Erosion and loss
	Geo-drainage mesh	HDPE drainage net	Collect and drain the leachate leakage of the upper membrane liner and control the liquid level on the lower membrane liner	Cracking		Leachate	Ll	CBPC
LDCS (Liu et al., 2021; Xu et al., 2023)	Drainage pipe	HDPE pipe	Collect and drain the leachate of the secondary drainage layer	1. Cracking 2. Clogging		L&T	LlUS	CL, SD, and OA
	Drainage standpipe	HDPE pipe	Collect and drain the leachate from the drainage pipe	Clogging	5	L&T	LlUS	CL, SD, and OA
	Water pump	Water pump	Discharge the leachate from the secondary drainage pipe	Cannot pump water		L&T	/	Corrosion and OA
	Flexible membrane liner	HDPE GMB	The second liner barrier for leachate leakage	HDPE GMB is damaged, and leaks occur		L&T	LlUS	SD and OA
SL (Brachman et al., 2008; R.Rowe et al., 2009)	Geotextile protective layer	Geotextile	Prevent HDPE GMB damage	1. Mechanical performance degrades 2. Permeability coefficient increases	3	L&T	LlUS	SD and OA
	Clay liner	Clay	Together with the HDPE GMB, it forms the second liner barrier	Permeability coefficient increases		L&T	LlUS	Erosion and loss
GCD (Kerry Rowe et al., 2023)	Drainage particles	Pebbles and gravel	Collect and drain the leachate leakage of the upper membrane liner and control the liquid level in the lower membrane liner	Cracking		Leachate	Ll	CL, SD, and OA
	Drainage pipe	HDPE pipe	Collect and drain the leachate of the secondary drainage layer	1. Cracking 2. Clogging	3	L&T	LlUS	CL, SD, and OA

RD = Rainwater drainage system; RLS = Rainwater liner system; GDS = Gas drainage system; LD = Leachate collection and drainage system; LDCS = Leakage detection and collection system; L&T = Leachate and temperature; USO = Uneven settlement of the overburden; DSPB = Differential settlement of the pile body; Ll = landfill load; LlUS = landfill load and uneven settlement; CL = Clogging; SD = Stress damage; OA = Oxidation aging; CBPC = Chemical, biological, and physical clogging; and GMB = Geomembrane.

3.2 Degradation effect

According to the FMMEA procedures, the impact of material failure was analyzed at the material level (the sub-subsystem level) first, followed by the impact at the previous level (the subsystem level), and finally the impact on the entire system.

On this basis, the severity level, failure mode probability, and detectability of failure were further analyzed. The definitions and descriptions of the failure mode severity level (Sankar and Prabhu 2001, Pillay and Wang 2003), failure mode occurrence probability, and failure detectability are shown in Table 3. The influence of each failure mode on the local, subsystem, and system (global) levels, as well as the severity level, failure probability, and detectability of each failure mode, were obtained. The results are shown in Tables 4 and 5.

Table 3 Criteria for evaluating the severity, probability, and detectability of failure modes (degradation factors) in FHWL systems

ID	Failure severity			Failure probability			Failure detectability	
	Category	Level	Description/criteria	Category	Level	Description/ criteria (occurrence probability)	Category	Level
1	Class I	Critical	The massive leakage of hazardous wastes or leachate causes catastrophic environmental consequences and huge economic losses	Class A	Frequently	≥ 20%	5	Near zero
2	Class II	Serious	FHWL is seriously damaged and cannot work normally, causing major economic losses	Class B	Sometimes	10%–20%	4	Extremely low probability
3	Class III	Concerning	Need to conduct maintenance and the occurrence of certain economic loss	Class C	Accidental	1%–10%	3	Low probability
4	Class IV	Minor	Results in unscheduled maintenance or repair and a small amount of economic loss	Class D	Rarely	0.1%–1%	2	Large probability
5	Class V	Slight	No significant impact on the performance of FHWL systems, or extremely easy to observe and repair	Class E	Very little	≤ 0.1%	1	Extremely high probability

The RSD system can effectively reduce the RD load of the closed greening system, thereby reducing the generation and leakage of leachate. The failure of the RSD system will lead to the failure of effective rainwater diversion, and off-site rainwater entering the landfill area may eventually lead to increased leachate production. However, because RSD failure is easy to detect and repair, its severity level is IV and its detectability were both 1. As a result, RSD failure should not be the priority focus of long-term performance evolution and life analysis.

The CG system mainly affects the landscape. A decline in the amount of vegetation may lead to changes in the underlying surface conditions, resulting in an increase in runoff, thus reducing the generation and leakage of leachate. From the perspective of landfill protection performance, the degradation of the greening system has little impact on leachate generation and leakage control, and may even have a positive impact. In addition, the degradation of the closed greening system is easy to detect. Considering its Class V severity level and Class I detectability, CG system failure should not be the priority focus of the long-term performance evolution and life prediction of the landfill.

Capping gas collection (CGC) systems are mainly used to collect and guide the gas in the landfill area. For FHWLs, landfill gas is not the focus of pollution control, and this is because the organic matter content in the landfill waste is very low, and the amount of methane, sulfur dioxide, carbon dioxide, and other gases produced by the anaerobic or aerobic reaction of organic matter is very small. Moreover, the drainage pipe failure probability of the CGC system is low, and the detectability is high. After comprehensive consideration, CGC failure was given a severity level of Class IV and a detectability level of Class III, and so should not be the focus of the long-term performance evolution and life prediction of the landfill.

The three collection and drainage systems (the rainwater collection and drainage system, the primary leachate collection and drainage system, and the secondary leachate collection and drainage system) are of great significance to leachate generation and leakage control, and their failure will adversely affect the overall performance of the landfill. Therefore, the failure of the main components of these systems (the collection and drainage medium, collection and drainage pipelines, and water pumps) was assigned a severity level of Class III. However, the clogging of collection and drainage pipelines is relatively easy to detect. Currently, two methods can be used to predict the failure modes of LSs. One method is a detection method that involves using the dipole method (Sun et al., 2019) and electrical resistivity tomography (Nai et al., 2019) to detect damage to HDPE GMB and the leakage of pollutants following the damage. The other method is a prediction method based on the Arrhenius equation (Lugt et al., 2023), combined with the operating temperature of the LS, to predict when the HDPE GMB will fail. Moreover, the dredging of the drainage pipeline can be accomplished by backwashing, so the drainage pipeline of each drainage system should not be the focus of the long-term performance evolution and life prediction of the landfill. Similarly, as the pump failure of the guiding and drainage system is easy to detect and repair, and the repair cost is not high, pump failure is not a concern. In contrast, it is difficult to clean and repair the drainage medium once it is silted. Therefore, the long-term evolution of the landfill performance and life prediction should focus on the drainage medium siltation of each drainage system.

The three LSs (the capping LS, primary leachate LS, and secondary leachate LS) are the core units of landfill leachate control and are of great significance in leachate generation and leakage control. Their failure will adversely affect the overall performance of the landfill. Therefore, the failures of their main components, the HDPE GMB and clay liner, were given severity levels of Class II and Class III, respectively. Although the geotextile protective layer of the LS can effectively buffer the HDPE GMB, it ages rapidly, causing it to deteriorate and lose its buffering and protection capacity shortly after the LS is installed. As a result, it only plays a role during the landfill construction period, and it is not the focus of life prediction. As a natural geotechnical barrier material, the clay liner in the barrier system usually has good aging resistance and a low probability of failure. Therefore, for each LS, the performance degradation of the HDPE GMB has a high failure severity level and is usually difficult to detect. Therefore, it should be regarded as a key target for long-term landfill performance evolution and life prediction.

Table 4 FHWL subsystem/subsystem failure impact analysis

Subsystem	Subsystem/component	Material	Degradation/failure effects			Severity	Probability	Detectability
			Local impact	Upper-level impact	Global impact			
RSD	Drainage	Ditch concrete	Off-site rainwater cannot be effectively diverted	The amount of off-site rainwater entering the entrance area increases	Increase in leachate production	IV	D	1
CG	Surface vegetation soil	Soil	Provide nutrition for vegetation	Vegetation decay and death	Reduced greening rate and damaged landscape	V	D	2
	Covering support soil	Soil	Provide support for vegetated soil			V	D	2
	Vegetation	Grass/trees	Vegetation decay and death	Reduced greening rate and damaged landscape		V	D	2
RD	Drainage medium Geo-drainage mesh	Pebble/gravel/geo-drainage mesh	Rainwater cannot be effectively drained	Water accumulation on the rainwater impervious layer increases	Increase in leachate production		C	3
RLS	HDPE GMB	HDPE GMB	Increase in rainwater infiltration	Increase in leachate production	Leakage of the primary liner layer increases	III	A	4
	Geotextile protective layer	Geotextile	Puncture resistance and reduced cushioning performance	The protection ability of the HDPE geomembrane decreases	HDPE GMB damage increases	IV	A	4
GDS	Gas collection and drainage pipe	HDPE pipe	Gas cannot be effectively exported	Gas is locally accumulated	-	IV	C	3
	Landfill	Hazardous waste	Solidification ability of curing materials decreases	Increase in leachate concentration	Environmental hazard increases after leakage	IV	B	3
LD	Filter layer	Fine sand/geotextile	Particle clogging filter	Formation of a discontinuous saturated zone	-	V	B	4
	Guide particles	Pebble/gravel	Pore space is blocked by particles and permeability is reduced	Decrease in the leachate conductive layer capacity	Leakage of the upper membrane liner increases	III	A	4
	Central spine drain	HDPE pipe				III	C	2
	Drainage branch	HDPE pipe				III	C	4
	Drainage standpipe	HDPE pipe				IV	D	1
	Water pump	Water pump	Water pump does not run	Elevated leachate level in the catchment pit		V	D	1
PL	Flexible membrane liner	HDPE GMB	Increase in leachate leakage	Water head rises above the lower membrane liner	LSI	II	A	4
	Geotextile protective layer	Geotextile	Puncture resistance and reduced cushioning performance	The protection ability of the HDPE geomembrane decreases	HDPE geomembrane damage increases	IV	A	4
	Clay liner	Clay	An increase in the permeability coefficient and a decrease in impermeability	The leakage from the upper membrane liner increases when the upper membrane liner is damaged	Leakage of the lower membrane liner increases	III	C	4

Subsystem	Subsystem/component	Material	Degradation/failure effects			Severity	Probability	Detectability
			Local impact	Upper-level impact	Global impact			
LDCS	Geo-drainage mesh	HDPE drainage net	Decrease in the liner performance	Leakage detection and drainage capacity decrease		III	A	4
	Drainage pipe	HDPE pipe	Pore space is blocked by particles and permeability is reduced	The water level of the leachate rises		III	C	3
	Drainage standpipe	HDPE pipe			Leakage of the upper membrane liner increases	IV	D	2
	Water pump	Water pump	Water pump does not run	Water level rise of the sump		V	D	1
SL	Flexible membrane liner	HDPE geomembrane	The second liner barrier for leachate leakage	Increase in leachate leakage	Increased risk of groundwater pollution	II	A	4
	Geotextile protective layer	Geotextile	Puncture resistance and reduced cushioning performance	The protection ability of the HDPE geomembrane decreases	HDPE geomembrane damage increases	IV	A	4
	Clay liner	Clay	An increase in the permeability coefficient and a decrease in impermeability	Leakage from the lower membrane liner increases when the lower membrane liner is damaged	LSI	III	C	4
GCD	Drainage particles	Pebbles and gravel	Reduced drainage capacity	Groundwater level rises	-	IV	D	3
	Drainage pipe	HDPE pipe	Groundwater cannot be collected in the drainage medium		-	IV	D	2

1 = Extremely high probability; 2 = Large probability; 3 = Low probability; 4 = Extremely low probability.

Table 5 Failure consequences of FHWL key components

System	Materials	Mechanisms	Function	Consequences of Failure		
				Local impact	Superior influence	Final consequence
RD	Drainage particles	Clogging	Rainwater level control	Decrease in the drainage capacity	The liquid level of the rainwater liner system rises	
RLS	HDPE GMB	Damage, aging	Leachate generation control	Rainwater infiltration	Control the increase in infiltration and increase in leachate production	
LD	Drainage particles	Clogging	Leachate level control	Decrease in the drainage capacity	Leachate accumulation and water level rise	
PL	HDPE GMB	Damage, aging	The main barrier against leakage		The leakage of the upper membrane liner increases, and the pressure of the secondary drainage and drainage and impervious layers increases	Leachate leakage and environmental pollution
LLD	Geo-drainage mesh	Clogging	Leakage detection of the main liner layer, reduced liquid accumulation, and reduced leakage risk		The detection effect decreases, the leakage in the secondary barrier system increases, and the leakage risk is the greatest	
SL	HDPE GMB	Damage, aging	Final barrier against leakage			

LLD = Leachate leakage detection system.

3.3 Key components and degradation mechanism

According to the above analysis, the drainage medium of the three drainage systems and the HDPE GMB of the three LSs have a high failure severity level, high occurrence frequency, and low detectability, and have an important impact on the overall performance of the landfill. Therefore, they were regarded as the key units of the long-term performance evolution and life prediction of FHWLs.

In the relatively simple degradation mode of the drainage medium, failure mainly occurs due to clogging. In contrast, the relatively complex degradation mode of the HDPE GMB is affected not only by the characteristics of the material itself, but also by factors such as light, temperature, oxygen, heat, water, mechanical stress, and high-energy radiation. Moreover, the degradation mode of the HDPE GMB is controlled by different degradation mechanisms. For any material, under the influence of different factors and degradation mechanisms, the degradation process and control mechanism are different, and the performance degradation prediction methods vary. Therefore, this section focuses on the failure mechanism and failure law of the HDPE GMB to explore its degradation mode in the landfill environment.

3.3.1 Basic characteristics of the HDPE GMB

HDPE resin is a thermoplastic resin produced by the copolymerization of ethylene that has high crystallinity and exhibits non-polarity. HDPE GMB is a plastic coil formed by blown GMB or the flat extrusion process from HDPE resin raw materials. In addition to polyethylene, HDPE GMB contains a certain proportion of carbon black and antioxidants. Carbon black is mainly used to prevent the photo-oxidative aging of HDPE GMB and ensure its stability in an environment with light. Antioxidants can prevent the oxidation of the HDPE GMB during use to ensure its long-term performance stability, and the content can reach 0.5% (Daniloska et al., 2010). The resin used to synthesize HDPE GMB is a linear copolymer obtained by polymerizing ethylene as the main monomer, adding a small amount of high-grade α-olefin, and using an appropriate type of catalyst in a low-pressure environment. The amount of α-olefin comonomer has a direct effect on the density of the resin; the greater the amount of olefin added during polymerization, the lower the density of the resulting polyethylene.

3.3.2 Deterioration mode of the HDPE GMB in the FHWL environment

Under ideal conditions—that is, those without sunlight, oxygen, acid–base liquids, or environmental stress—HDPE GMBs designed, constructed, and installed under strict quality control and quality assurance measures are intact and have excellent impermeability. However, under actual service conditions, polymers are exposed to complex chemical and stress environments, and their long-term use may lead to the damage and performance degradation of polymeric materials, eventually causing failure. Due to the wide range of different engineering application scenarios, HDPE GMBs may be exposed to different environmental and stress conditions, resulting in different types of performance degradation. Therefore, the deterioration mechanisms of geomembranes under different environmental conditions reported in the relevant literature were collected and collated, and the possible deterioration modes of GMBs and their control mechanisms were obtained, as shown in Table 6.

Table 6 Deterioration mechanism and consequences of the HDPE GMB under different environmental and stress conditions

Influencing factors	Occurrence stage	Source	Aging mechanism	Failure condition	Landfill actual conditions	Possibility of occurrence	Aging consequences
Transient overstress (Berger 2015)	Installation and operation process	Excessive instantaneous stress, such as tearing by construction machinery, piercing by sharp stones, and tree roots	Overstress	Defects or loopholes caused by overstress damage become the preferred channel for leachate leakage, resulting in a significant decline in seepage prevention performance.	During the production, transportation, installation, and even use of the HDPE GMB, various sharp objects may cause overstress damage.	Probable	Piercing and tearing
Light (+ oxygen) (Rowe and Sangam 2002, Kyrikou, Briassoulis et al. 2011)	Setup script	Ultraviolet and visible light	Ultraviolet degradation	The polymer is degraded by photooxidation under the action of ultraviolet rays	The HDPE GMB contains carbon black, which can resist ultraviolet aging, and has a 15–30-cm soil covering on the GMB	Possible	Discoloration, surface cracking, embrittlement, and deterioration of mechanical properties
High-energy radiation (Tian, Benson et al. 2018)	Operation stage	Radiation generated by low-level radioactive wastes in hospitals and laboratories	Radiation cleavage	When the ionizing radiation of penetrating particles has enough energy to exceed the carbon–carbon bond energy, it will damage the structure of the polymer.	The bond in the HDPE GMB polymer is affected by α and β particle damage, leading to antioxidant consumption	Possible	Polymer molecular chain breaks, tensile strength decreases, and fission products are produced
Water	Installation and operation process, post-closure	Rainfall and leachate	Dissolution	Polymer materials will expand to a certain extent when immersed in water (pH = 7) or when in contact with water	The concentration of pollutants in the FHWL leachate is less than that in the laboratory swelling test solution.	Possible	The volume of the HDPE GMB increases, but the process is reversible
pH effects	Operation process	Leachate: highly acidic (pH < 3) or highly alkaline (pH > 12)	Chemical degradation	Destroy the plastic GMB lining and related synthetic materials (polymer)	HDPE GMB has excellent acid and alkali resistance.	Possible	
Microorganisms	Operation stage	Bacteria and microorganisms in soil or solid waste	Biological degradation	The brittleness of the geomembrane increases due to the extraction of antioxidants	The polymer of the HDPE GMB is extremely unlikely to be degraded by microorganisms	Unlikely—improbable	Fracture of the polymer molecular chain and decrease in tensile strength
Constant external stress	Installation and	Construction machinery rolling, fold + pressure,	Creep		HDPE joints have a high incidence of fracturing, while fracturing in other locations rarely occurs.	Probable	Deformation and serious fracture

(Yang, Xue et al. 2017)	operation process	thermal expansion, and cold contraction tensile force, as well as slope, anchor ditch, leachate sump, and other stress concentration parts, slope destabilization		HDPE GMB deforms and damages under long-term constant stress			
Leachate (Koerner, Hsuan et al. 2007)	Operation process	Ions or organics in leachate	Extraction degradation	The brittleness of the geomembrane increases due to the extraction of antioxidants	The geomembrane is filtered by the stabilizer and antioxidant, and the material is oxidized and degraded.	Possible	Stabilizers and antioxidants lead to more oxidative degradation
Heat (+ oxygen) (Koerner 2016)	Installation and operation process and after site closure	Environmental temperature, heat generated by solid waste hydration, and heat generated by organic matter fermentation	Oxidation degradation	The mechanical properties of the polymer decrease, and at high temperatures greater than 200°F (approximately 93.3°C), the oxidation is rapid	When the landfill temperature reaches 70°C, the oxidation degradation and performance degradation of the HDPE GMB are serious	Probable	Antioxidant consumption, polymer molecular chain breakage, molecular weight reduction, and engineering properties decline

Table 6 shows that ultraviolet aging, high-energy radiation, swelling degradation, pH, biodegradation, creep, and extraction degradation have a low probability of occurrence and a relatively small impact on the HDPE GMB. Due to their high occurrence probability and serious degradation consequences, overstress damage (physical damage) and oxidative aging were identified as the HDPE GMB degradation modes in the FHWL service environment.

Oxidative degradation reduces the mechanical properties of polymers and makes them brittle, and is thus considered the most important and harmful type of degradation occurring in the HDPE GMB at the bottom of a landfill (Guo et al., 2018, Majewski et al., 2020). The oxidation process of a polymer is essentially a radical chain reaction. In the initial stage of this process, the main effect is physical, and the mechanical engineering properties of the material exhibit no obvious change. In the later stage, this process gradually shifts to chemical action, the molecular chain of the polymer starts to break, the molecular weight decreases, and the mechanical engineering properties gradually decrease (such as the tensile modulus, fracture stress, and strain), until the material finally fails. In addition, oxidation is greatly affected by temperature. At a high temperature of more than 200°F (approximately 93.3°C), oxidation is rapid. The degradation of organic matter and the hydration of fly ash and solidified substrate in the landfill environment generate a great amount of heat, and the stack temperature can reach 70°C. Under these temperature conditions, the oxidative degradation of the HDPE GMB and its performance degradation require special attention. A series of corresponding measures can be implemented either before or after the occurrence of these failures to delay the oxidation degradation of HDPE GMB, especially for FHWLs that have existed for a long period of time. All polymers undergo photodegradation under UV irradiation, with the main UV spectral wavelength causing polymer degradation located in the UV-B region (315–380 nm) (ROWER et al., 2002). In the processing of HDPE GMB, a specific proportion of blocking or screening agents, such as carbon black, is usually added to effectively absorb and scatter ultraviolet rays, thereby delaying the degradation caused by ultraviolet radiation (T.L. Phease et al., 2000; Wai et al., 2014). However, the ratio of added carbon black needs to be carefully controlled, and is usually maintained at 2–3%. This is because excessive carbon black content may have adverse effects on the mechanical properties of HDPE GMB, and when the carbon black content reaches a certain level, its ability to resist UV aging tends to become saturated. In addition, studies have shown that covering an HDPE GMB with 15–30 cm of soil is sufficient to prevent the most significant effects of ultraviolet radiation (Sun et al., 2019). Therefore, for geotextiles such as HDPE GMB, timely covering with soil within 6–8 weeks after construction is an effective protective measure. In addition to the soil covering strategy, researchers are currently exploring other strategies (Werner Mueller et al., 2003), such as the adhesion of geotextiles to the surface of HDPE GMB to enhance their UV aging resistance.

Field tests and laboratory experiments have shown that even a scientifically designed and well-constructed LS cannot guarantee that HDPE GMBs in landfills will not exhibit any defects. HDPE GMBs can suffer overstress damage due to various sharp objects during production, transportation, and installation. Additionally, slope destabilization leads to pile deformation, causing tearing damage to the HDPE membrane. According to the stage of the overstress damage, defects can be classified as origin defects, pinhole defects, installation defects, or operational damage (Berger et al., 2015). Among these defects, origin defects generally arise during the manufacturing process. Origin defects are smaller defects, with thicknesses less than that of the geomembrane thickness (generally 0.001 m or slightly larger). Installation defects occur during the geomembrane-laying and guide-drain gravel-laying processes. These defects are caused by breakage due to installation machinery, as well as debris and tree roots. Operational damage occurs during landfill operation due to mechanical filling or uneven settlement of the pile, and is caused by cracked welds. Considering the consequences of deterioration, once there is a breakage in the HDPE GMB due to mechanical damage or a hole, the breakage becomes a priority channel for leachate leakage and the barrier function is significantly reduced.

4 Implications

4.1 Implications for cleaner production

The research indicates that landfills, especially FHWL, have a limited service life, after which the emission of leachate and pollutants significantly increases upon the expiration of their lifespan. Therefore, from the perspective of clean production, the following measures need to be taken. First, it is necessary to reconsider the emission of pollutants from landfills from a whole life cycle perspective, not just during the operation and closure phases, but also including the increase in emissions caused by the degradation of pollution barrier performance after the service period. Second, governments and society, especially landfill owners, need to re-examine the positioning of landfills. They should be considered as a long-term storage method for solid waste rather than a once-and-for-all final disposal method. This also indicates that the end point of the life of solid waste, especially the waste that has been landfilled, should be resource recovery, not landfills. Only through resource recovery can the emission of pollutants from solid waste be minimized as much as possible. Third, from the perspective of reducing the emission of pollutants during the solid waste landfill process, it is necessary to adopt some design and operational optimization techniques and engineering measures to slow down the rate of performance degradation of landfills, reduce the emissions of pollutants caused by performance deterioration, and improve the efficiency of landfills as an engineering facility.

4.2 Direction for future work

The research indicates that landfills have a limited lifespan. Therefore, studies should be conducted on landfill lifespan prediction, life extension measures, and emergency response after the lifespan expires, including: (1) Developing methods for predicting the design lifespan of landfills, quantitatively assessing the performance degradation, risk evolution, and lifespan characteristics of landfills, and identifying the main driving factors and laws; (2) Establishing methods for monitoring the operational state of landfills and predicting their remaining lifespan, to better identify landfills whose lifespan has expired or is about to expire, and to formulate appropriate response measures in advance; (3) Proposing life extension measures based on design and operational optimization, to extend the service life of landfills as much as possible, prevent the increase in pollutant emissions and the loss of landfill capacity caused by rapid performance deterioration, and improve the efficiency of landfill use.

5. Conclusions

(1) According to the definition and structural composition of the FHWL system, the FMMEA method was used to identify the failure mode of each underlying system based on the functions, material characteristics, service environment conditions, and stress conditions of each component. A total of 33 degradation factors and 35 corresponding potential failure modes were identified.

(2) Among all possible failures, the failure of the drainage medium in the three drainage systems and the HDPE GMB in the three LSs will most adversely affect the overall performance of the landfill. Guiding and drainage media are not easy to clean and they do not easily recover after clogging. Moreover, the failure of the HDPE GMB occurs easily, is difficult to detect, and leads to serious performance degradation. Therefore, these two failures are the key targets of FHWL long-term performance evolution and life prediction.

(3) The degradation characteristics of key components are different under various environments and stress conditions. The relatively simple degradation mode of the guiding and discharging medium mainly occurs due to siltation; however, the relatively

complex degradation mode of the HDPE GMB is affected not only by the characteristics of the material itself but also by light, temperature, oxygen, heat, water, mechanical stress, and high-energy radiation. Among these factors, overstress damage and oxidative aging were identified as the most important degradation modes of the HDPE GMB in the FHWL service environment due to their high probability of occurrence and serious degradation consequences.

(4) This study systematically explores and identifies the failure modes and mechanisms of FHWLs, providing direction for future improvements in landfill performance, prolonging service life, and early fault diagnosis technology development. The research results also highlight the importance of optimizing design and operational strategies in achieving cleaner production in landfills and reducing environmental impacts. Furthermore, the study suggests a reexamination of the traditional perception of landfills as endpoints for solid waste management, supporting the transition towards waste management strategies focused on resource recovery. It provides scientific evidence for the development and application of clean production technologies in the field of solid waste management.

Author contributions

Panpan Qiu: Methodology, Formal analysis, and Writing—Original draft. **Ya Xu:** Conceptualization, Resources, Writing—Review, Editing, and Funding acquisition. **Guangyuan Yao:** Manuscript revision. **Yuqiang Liu:** Provision of resources. **Lu Dong:** Formal analysis. **Qifei Huang:** Methodology. **Jingjing Wang:** Manuscript revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- Identified 35 failure modes and over 60 failure mechanisms behind them in landfill
- Ascertained 2 key units affecting FHWL life considering their failure impact
- Overstress damage and oxidative aging are key degradation modes for HDPE geomembrane

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: