Geotextiles and Geomembranes 53 (2025) 744–753

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Regular Paper

Generation and prediction of defect in HDPE GMB serving as landfill base barrier

Feng Yang [a,b,e], Jingcai Liu [a,b], Ting Lin [a,b], Changxin Nai [a,b,c], Yuqiang Liu [a,b], Panpan Qiu [d], Ya Xu [a,b,*], Can Qian [a,b,**]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[b] Environmental Protection Key Laboratory of Hazardous Waste Identification and Risk Control of Ministry of Ecology and Environment, Beijing, 100012, China
[c] School of Information and Electronic Engineering, Shandong Technology and Business University, Yantai, Shandong, 264005, China
[d] School of Information and Communication Engineering, Beijing University of Technology, Beijing, 100124, China
[e] School of Environment, Tsinghua University, Beijing, 100084, China

ARTICLE INFO

Keywords:
Landfill
HDPE GMB
Initial defect
Prediction model

ABSTRACT

This study utilized electrical defects detection, correlation analysis, and regression analysis to conduct a prediction about the generation of defects in high-density polyethylene geomembranes (HDPE GMBs) in landfills. The findings revealed that the average defect density of 108 landfills was 15 defects/ha, and the average defect area was 122 cm^2/ha. Four out of the 11 potential indicators, namely construction unit qualification, HDPE GMB thickness, drainage media type, and drainage system structure, had a significant impact on the density of installation and total defects. Prediction models of installation and total defects, using the four key indicators as independent variables, could reasonably predict the occurrence of initial defects. The model supports the accurate prediction of landfill risk and the identification of high-risk sites, which is crucial for hierarchical classification management and risk control.

1. Introduction

Landfilling is the primary method of solid waste disposal in many countries, particularly emerging economies, due to the properties of simple technical principles and ease of operation (Sekhohola-Dlamini and Tekere, 2020). In China, the landfill volume of the municipal solid waste peaked at 120 million tons per year in 2017 and then began to decline, although it is still maintained at the level of 100 million tons per year. Even in developed economies, landfills are still irreplaceable for the final disposal of solid waste. In the United States, 52.6% of the 2.34 million tons of hazardous waste generated yearly is disposed of in landfills (Sun et al., 2019), and more than 23% of municipal solid waste in the EU is landfilled (Eurostat, 2019).

Landfills represent a major source of secondary pollution and pose risks to the population and environment, if the leachate leaks when the High-density polyethylene geomembranes (HDPE GMBs) defects generate. Leachates with complex components, high concentrations, and varying degrees of toxic and persistent pollutants, such as heavy metals and persistent organic pollutants (POPs), are formed during landfilling (Kjeldsen et al., 2002; Nie et al., 2021), and leakage will cause significant contamination to surrounding soil and groundwater (Amano et al., 2020). HDPE GMBs may be affected by various factors during landfill design, construction and operation, resulting in HDPE GMB defects and damages. Although the damage degree is different, all of the defects can cause leakage and eventually increase the possible risk of groundwater pollution. The more leakage there is, the greater the risk is (Xu et al., 2014). In developing countries, due to inadequate quality control measures during landfill construction and operation, more serious damage to the HDPE GMB is caused (Mohammad et al., 2017; Morita et al., 2021). For example, HDPE GMBs have 17 to 19 defects per hectare for 80 landfills in China on average (Xu et al., 2015). Developed countries such as the United States and those in Europe have strong

* Corresponding author. State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
** Corresponding author. State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
E-mail addresses: yang.feng@craes.org.cn (F. Yang), wdf04@163.com (J. Liu), 978238083@qq.com (T. Lin), ncx_lab@163.com (C. Nai), liuyq@craes.org.cn (Y. Liu), qpp17658093323@163.com (P. Qiu), xuya@craes.org.cn (Y. Xu), qian.can@craes.org.cn (C. Qian).

https://doi.org/10.1016/j.geotexmem.2025.01.009
Received 18 February 2024; Received in revised form 7 January 2025; Accepted 31 January 2025
Available online 9 February 2025
0266-1144/

environmental awareness, and defects in the HDPE GMB in these countries are generally possible reduced to three holes per hectare through strict quality control and guarantee measures (Xu et al., 2019; McQuade and Needham, 1999). In addition, groundwater contamination still occurs around landfills in certain developed countries such as the United States, with over 70% of landfills were found concentrations of certain contaminants exceeding the limits in the groundwater standards. (Xu et al., 2019; Saeedreza et al., 2017).

The risk of potential groundwater contamination increases the necessity to accurately predict the number of defects in HDPE GMBs. If the number of defects is accurately predicted, it will help to predict the life-cycle emissions of landfills more accurately, identify landfills with high leakage risks, and take targeted control measures. For this reason, much research has been conducted on this topic. Some scholars have combined the hydrological performance model with the pollutant migration and diffusion model, taking the number of HDPE GMB defects as the key input parameter to quantitatively analyze the leachate leakage and its migration and distribution in groundwater under different defect conditions. Barakat et al. (2024) evaluated the diffusion coefficient for PFOA and PFOS migration through GCL's and composite liners used in landfills by diffusion test. Naveen et al. (2018) estimated the transport and dispersion of leachate pollutants and assessed the risk of contamination considering the physicochemical properties of water and soils. Lentz (1981) and Xiang et al. (2020) presented a prediction model to calculate leakage and predict groundwater contamination risk with the number of defects as a key parameter. Xue et al. (2006) established a leachate risk assessment and prediction model by comprehensively considering the factors such as leakage points, leakage paths, and diffusion trends, and quantitatively analyzed the pollution diffusion problem.

Most previous studies have predicted leachate leakage and its potential risks based on the number of defects obtained directly from field detection in landfills with single composite liners. However, this method is only applicable to landfills that have laid HDPE GMBs but have not disposed of waste. For landfills that have buried waste, the number of defects in HDPE GMBs cannot be detected using the existing technology due to the variability of the induced signals decreases and therefore needs to be determined through models and experience. For example, Drury et al. (2003) analyzed the defect characteristics in HDPE GMBs at hundreds of landfills and established a probability distribution model. However, how to quantitatively assess the number or density of HDPE GMB defects according to HDPE GMB materials, impermeable structure, construction, and operation at the landfill site remains a key technological challenge that needs to overcome in the analysis of leachate leakage and pollution risk. To build a quantitative prediction model for defect generation and evolution, this study detected and located the defects in HDPE GMBs in 108 landfills and computed the defect density for each landfill. This work further identified the major indicators influencing the generation of defects. Based on these, we constructed a multiple regression model for the prediction of the number and density of defects in HDPE GMBs and extended the model to the defect prediction of the entire HDPE GMB life cycle.

2. Materials and methods

2.1. Initial defect location and landfill selection

The electrical method recommended by the Environmental Protection Agency (EPA) (EPA, 1989) was used to locate the defects in HDPE GMBs installed in landfills. This method was based on the high resistance characteristics of HDPE GMBs (Nai et al., 2005, 2006). A high-voltage current excitation source was applied on both sides of the GMB, and a dipole device was used to acquire a potential signal in a medium above the GMB to obtain the potential spatial distribution. When a defect or hole existed in the HDPE GMB, the potential presented a local abnormality so that the defect or hole could be located (Guan et al., 2010). All defect detections were performed after the geotextile and drainage layer were placed over the landfill HDPE GMB, and the total thickness of the geotextile and drainage layer was less than 50 cm, which did not affect the defect detections.

Fig. 1. Distribution of landfills.

After detecting, the geotextile and drainage media laid on the HDPE GMB were manually cleaned and removed, and the location was checked for defects. If defects existed, the parameters were measured and recorded, such as the number of defects, the diameter of the defects, the area of the defects, and the area of the landfill detection.

For the establishment of the analysis and prediction model, defect data from 108 landfills in total were used. Fig. 1 illustrates the locations of these landfills, which span seven geographical areas, including 16 provinces in China, representing distinct economic levels and lifestyles. The area of each landfill and the detected defects are shown in Table 1. The defect detection process followed the methods and procedures outlined in ASTM D6747-15 and ASTM D7007-16 for preparation. Defect detection was performed and quality control was implemented to ensure that all defects could be detected to the greatest extent possible.

2.2. Initial defect characterization

It has been shown that defects less than 1 mm in diameter have a completely different leakage pattern to defects larger than 1 mm and require different formulas to predict their leachate leakage (Rowe, 2018). Therefore, density statistics were calculated separately for defects below 1 mm (known as pinhole defects) and defects above 1 mm (known as non-pinhole defects). For each landfill, the defect area per hectares of HDPE GMB was also calculated.

The detection data shown in Table 1 were used for defect characterization. For each landfill, the pinhole defects in a unit area (PDUA), non-pinhole defects in a unit area (NDUA), total defects in a unit area (TDUA), and the defect area in a unit area (DAUA) were determined, as follows:

$$\begin{cases} PDUA = \dfrac{N_{pin}}{A_T} \\ NDUA = \dfrac{N_{non}}{A_T} \\ TDUA = \dfrac{N_T}{A_T} \\ DAUA = \dfrac{A_d}{A_T} \end{cases}, \tag{1}$$

where N_{pin} is the total number of pinhole defects (defect diameter d less

Table 1
Statistical table of detection data.

Number	Province	Number of pinhole defects[a]	Number of non-pinhole defects[a]	Total number of defects[a]	Total defect area[b]	Detection area[b]
1	Anhui	0	3	3	1.1	3900
2	Anhui	0	3	3	17	6000
3	Anhui	0	6	6	53.5	10000
4	Anhui	0	7	7	3.6	13000
5	Anhui	0	8	8	14	9600
6	Anhui	1	5	6	2.1	6000
7	Anhui	2	20	22	35.34	39000
8	Chongqing	0	2	2	0.8	3000
9	Chongqing	0	15	15	4790.8	26000
10	Guangdong	0	14	14	14	4800
11	Guangdong	2	9	11	8472	9975
12	Guangdong	37	0	37	14	4800
13	Guangxi	0	6	6	1100.3	3000
14	Guangxi	0	8	8	2133.4	15000
15	Guizhou	0	0	0	0	700
16	Guizhou	0	1	1	0.6	4500
17	Guizhou	0	2	2	602	1000
18	Guizhou	0	4	4	55.4	3000
19	Guizhou	0	5	5	11.1	4000
20	Guizhou	0	5	5	14	4300
21	Guizhou	0	8	8	70.3	6500
22	Guizhou	0	8	8	17.5	3100
23	Guizhou	0	10	10	616	4000
24	Guizhou	0	10	10	511.5	2570
25	Guizhou	0	10	10	387	4350
26	Guizhou	0	10	10	55	20000
27	Guizhou	0	11	11	203.4	7200
28	Guizhou	0	12	12	86.6	5310
29	Guizhou	0	12	12	29255	3700
30	Guizhou	0	13	13	21.6	10000
31	Guizhou	0	20	20	0.6	3000
32	Guizhou	0	22	22	48	7000
33	Guizhou	0	29	29	1266.2	11000
34	Guizhou	0	47	47	264.6	7200
35	Guizhou	0	60	60	15700.8	10200
36	Guizhou	1	0	1	200.8	2100
37	Guizhou	1	3	4	0.5	7800
38	Guizhou	1	4	5	0.7	9000
39	Guizhou	1	4	5	5.7	7000
40	Guizhou	1	4	5	16	1400
41	Guizhou	1	6	7	8.2	3800
42	Guizhou	1	10	11	9.7	5500
43	Guizhou	1	12	13	29	6500
44	Guizhou	1	13	14	412.6	4300
45	Guizhou	1	20	21	422.5	6600
46	Guizhou	1	25	26	1228	7800
47	Guizhou	1	97	98	21091.9	15000
48	Guizhou	2	2	4	1.3	4500
49	Guizhou	2	4	6	14	9600
50	Guizhou	2	5	7	1007	4700
51	Guizhou	2	6	8	1070	7100
52	Guizhou	2	8	10	1065	17000
53	Guizhou	2	12	14	19.9	29500
54	Guizhou	2	13	15	4.7	9000
55	Guizhou	2	14	16	699.5	13700
56	Guizhou	2	36	38	129.8	11600
57	Guizhou	3	3	6	1	4700
58	Guizhou	3	13	16	45.4	3000
59	Guizhou	3	21	24	232.3	8200
60	Guizhou	4	17	21	416	11000
61	Guizhou	4	18	22	206.6	10800
62	Guizhou	4	49	53	5507.5	14000
63	Guizhou	5	13	18	517.4	6100
64	Guizhou	5	65	70	97.8	6000
65	Guizhou	6	7	13	12	8400
66	Guizhou	6	25	31	13.5	3200
67	Guizhou	6	29	35	7525	3200
68	Guizhou	8	1	9	0.3	4000
69	Guizhou	8	2	10	3.2	8600
70	Guizhou	9	18	27	6.4	11700
71	Guizhou	10	136	146	10179.44	12000
72	Guizhou	11	26	37	29.7	13000
73	Guizhou	13	27	40	145	13300
74	Guizhou	32	32	64	11.84	20016.34

(continued on next page)

Table 1 (*continued*)

Number	Province	Number of pinhole defects[a]	Number of non-pinhole defects[a]	Total number of defects[a]	Total defect area[b]	Detection area[b]
75	Hebei	0	1	1	0.4	4000
76	Hebei	0	2	2	0.7	4000
77	Hebei	0	29	29	182	20000
78	Hunan	1	24	25	4811.1	19500
79	Jiangsu	0	1	1	0.3	13780
80	Jiangsu	1	11	12	100	6075
81	Jiangsu	16	0	16	16	43000
82	Jiangxi	0	2	2	12	10000
83	Jiangxi	0	4	4	4	41000
84	Liaoning	0	1	1	10	2400
85	Ningxia	0	84	84	350	5500
86	Ningxia	1	7	8	1560	25800
87	Shandong	3	54	57	28109.8	88000
88	Shandong	16	200	216	254649.07	26000
89	Shaanxi	0	4	4	0.8	7000
90	Shaanxi	0	4	4	18	4500
91	Sichuan	0	5	5	3.6	2800
92	Sichuan	0	15	15	1763.04	20000
93	Sichuan	0	26	26	254.5	14000
94	Sichuan	1	5	6	2.9	2100
95	Sichuan	1	14	15	213.4	13000
96	Sichuan	2	1	3	0.6	28000
97	Sichuan	2	3	5	1000.3	10000
98	Sichuan	5	20	25	103.38	7600
99	Sichuan	6	132	138	112345.5	26000
100	Sichuan	9	6	15	16	34000
101	Zhejiang	0	0	0	0	2000
102	Zhejiang	0	8	8	3.5	23800
103	Zhejiang	0	13	13	14	11000
104	Zhejiang	1	3	4	402.3	6680
105	Zhejiang	2	2	4	10	3400
106	Zhejiang	3	14	17	203.64	17000
107	Zhejiang	4	14	18	8.1	6100
108	Zhejiang	48	662	710	373193.12	84300

Note: 1) [a]The number of defects is given in pieces. [b]The total defect area is in cm^2, and the detection area is in m^2.
2) All defect detections were performed after the geotextile and drainage layer were placed over the landfill HDPE GMB.

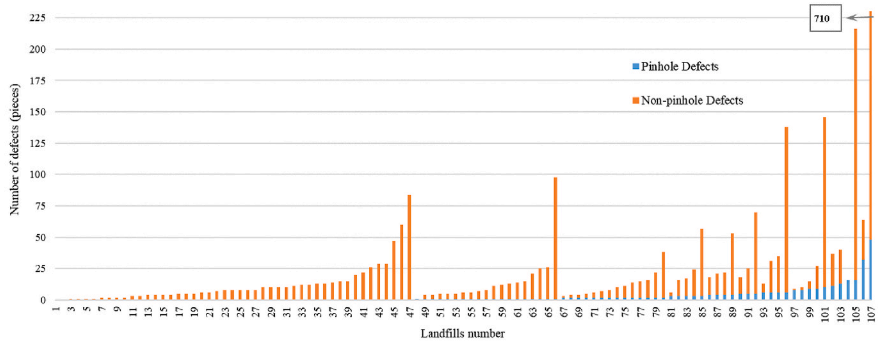
Table 2
Indicator assignment.

Criterion	Factor	Name	Assignment	Classification	Value
Materials and design	x_1	Production region of high-density polyethylene geomembrane (HDPE GMB)	Overseas regions, Hong Kong, Macao, and Taiwan	1	/
			Domestic	2	
			Shandong	3	
			Unknown	4	
	x_2	drainage system structure	More than two protective layers between drainage particles and HDPE GMB	1	$x_2 = 1$
			No drainage particles	2	$x_2 = 1$
			Less than or One protective layer between drainage particles and HDPE GMB	3	$x_2 = 0$
	x_3	HDPE GMB thickness	≥2 mm	1	$x_3 = 1$
			1.5 mm and below	2	$x_3 = 0$
	x_4	Landfill type	Plain	1	/
			Mountain valley	2	
	x_5	Drainage media	Pebbles (20–50 mm)	1	$x_5 = 1$
			No drainage particles	2	$x_5 = 0$
			Gravel (20–50 mm)	3	$x_5 = 0$
Construction and management	x_6	Qualification of construction units	With professional engineering construction qualifications	1	$x_6 = 0$
			With professional anti-seepage construction qualifications	2	$x_6 = 0$
			General constructions	3	$x_6 = 1$
			Other constructions	4	$x_6 = 1$
	x_7	Landfill area	Municipal landfills in underdeveloped areas, County/city landfills in developed areas	1	/
			County landfills in non-developed areas	2	
Landfill size	x_8	Service life	Continuous variable, assigning values based on actual service life		/
	x_9	Total storage capacity	Continuous variable, assigning values based on actual total storage capacity		/
	x_{10}	Daily treatment capacity	Continuous variable, assigning values based on actual landfill capacity		/
	x_{11}	Area at bottom	Continuous variable, assigning values based on the actual area		/

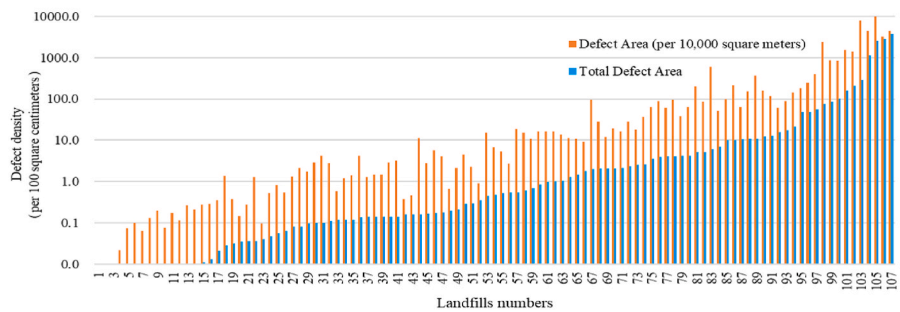
than 1 mm); A_T is the real HDPE GMB detection area at the bottom of a landfill, hm^2; N_{non} is the total number of non-pinhole defects (d greater than 1 mm); N_T is the total number of defects ($N_T = N_{non} + N_{pin}$); and A_d is the total defect detection area, cm^2.

2.3. Correlation analysis

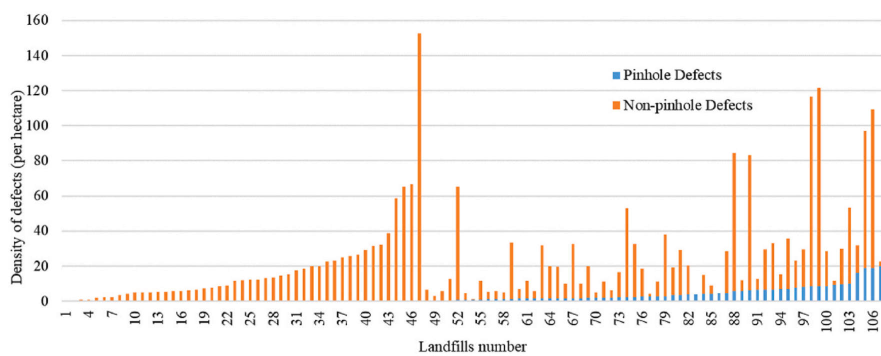
The causes and patterns influencing the defects of HDPE GMBs were researched, and 11 variables that might impact the defect generation



(a) Number of pinhole defects (d < 1 mm) and non-pinhole defects (d >1 mm)



(b) Defect area of HDPE GMBs



(c) Density of pinhole defects and non-pinhole defects

Fig. 2. High-density polyethylene geomembrane (HDPE GMB) defect detection results in China.

were found, categorized into materials and design factors, construction and management factors, and landfill size factors, as presented in Table 2. The classification assigned to each indicator is based on the actual situation of the indicator, which in general includes 2 types of indicators, one is continuous and the other is discontinuous. Taking the continuous indicator of total storage capacity as an example, the classification of the indicator is equal to the actual value of the landfill capacity; while for the discontinuous indicators such as the landfill type, the actual investigation shows that it usually contains plain-type landfill and mountain valley-type landfill, so the assigned classifications are 1 and 2 which correspond to the plain-type landfill and the mountain valley-type landfill, respectively. Regarding the HDPE GMB production region, we consider that HDPE GMBs produced in different regions may have different raw materials and processes, which could result in varying numbers of original defects and fragility. Especially, previous investigations have indicated that some HDPE GMBs in Shandong frequently use recycled materials. Therefore, we have listed the surveyed HDPE GMB production regions and attempted to separate Shandong province.

Key contributing elements were discovered to quantitatively measure indexes' influence on HDPE GMB defects. Correlation analysis was used to study continuous variables in this work. Errors may occur in the actual collected data and should be judged with a significance test. A correlation coefficient (or its absolute value) between an influencing indicator and the defect characterization of HDPE GMB near 1 indicated a high correlation. Assuming a significance level $\alpha = 0.05$, if the significance test results are smaller than α, then there is a significant difference between the two groups. High-relevance indicators should be

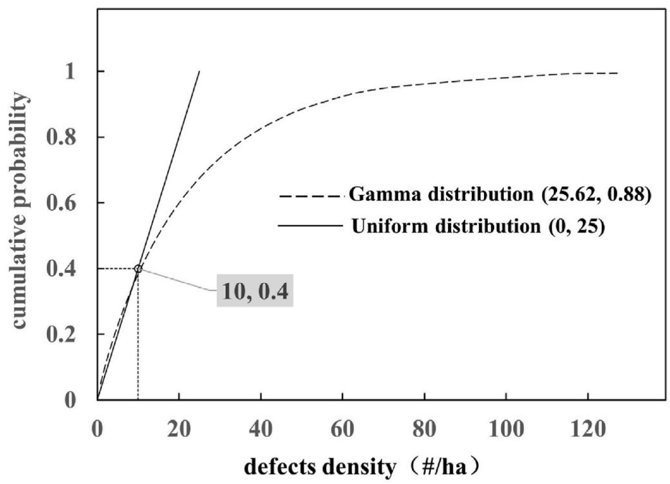


Fig. 3. Comparison of cumulative probability of Uniform (0, 25) distribution and Gamma (25.62, 0.88) distribution.

considered when establishing the prediction model, and low-relevance indicators will be eliminated. Regarding the correlation between discontinuous variables and defect characteristic indicators, the method of contingency correlation analysis is used. For instance, the defect density is divided into 6 grades with an interval of 20/ha, then combined with different classifications of a discontinuous variable, a contingency table can be constructed. Specifically, columns represent different grades of defect density, and rows represent different classifications of a discontinuous variable. Subsequently, the frequency of observations that belong to both the row and column categories simultaneously is record in each cell. Finally, according to the contingency coefficient and the significance test results, the correlation between the discontinuous variables and the defect density characteristics was judged, and the discontinuous variables that affect the defect characteristics were identified.

2.4. Construction of prediction model for initial defects

Multiple regression models were utilized to depict the relationship between the quantity or density of defects and influencing factors. Assuming a linear relationship exists between the number or density of defects and the influencing factors, their connection can be portrayed by the following linear equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p + \varepsilon \tag{2}$$

where y is the dependent variable, corresponding to the defect characterization index in this paper; β_n is the parameter to be fitted, with n = 0,1, …, p; β_0 is the constant term; x_n is the independent variable with n = 1, …, p (e.g., HDPE GMB thickness, the type of drainage media, and the drainage system structure); and ε is the random error.

The least square method is used to determine the regression coefficients in the linear equation due to its simple principle, faster convergence, and easy to understand and implement for solving curve fitting problems (Wang et al., 2024). Its basic principle is to find the estimated values of parameters by using the observed data of different landfills obtained from field investigation, and the estimated value must meet formula (3). The observed data includes independent variables, such as HDPE GMB thickness, type of conduction medium, etc., and interpreted variables, such as defect quantity, defect density, etc.

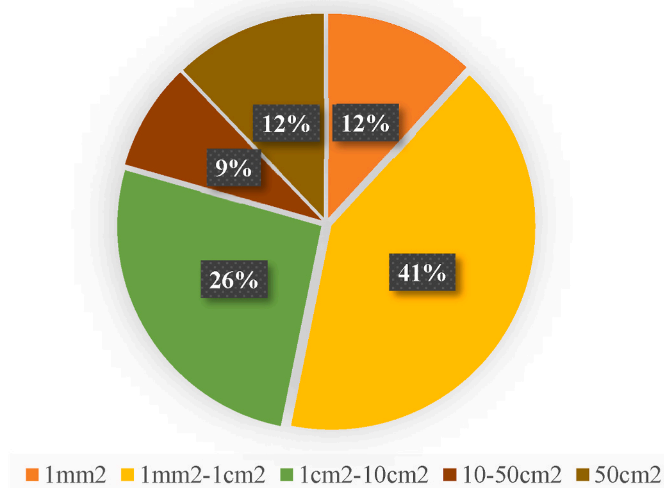


Fig. 4. The proportion of defects in different sizes on HDPE geomembrane.

$$Q\left(\widehat{\beta}_0, \widehat{\beta}_1, \widehat{\beta}_2, \cdots, \widehat{\beta}_p\right) = \sum_{i=1}^{n}\left(y_i - \widehat{\beta}_0 - \widehat{\beta}_1 x_{i1} - \widehat{\beta}_2 x_{i2} - \cdots - \widehat{\beta}_p x_{ip}\right)^2$$
$$\min_{\beta_0,\beta_1,\cdots,\beta_p} \sum_{i=1}^{n}\left(y_i - \beta_0 - \beta_1 x_{i1} - \beta_2 x_{i2} - \cdots - \beta_p x_{ip}\right)^2 \tag{3}$$

3. Results and discussion

3.1. Occurrence, density and scale of initial defect in HDPE GMB

The defect characterization data for each landfill was shown in Fig. 2. It is found that 3213 defects with a total area of 15311 cm^2 were detected in 108 landfills with a total area of 1,255,000 m^2. It is estimated that the average number of defects per is 15, and the average area of defects per hectare is 122 cm^2.

The cumulative distribution of defect density in landfills is shown in Fig. 3. It can be seen from the Figure that the defect density of Chinese landfills follows the Gamma distribution (25.6,0.88). Compared with the cumulative probability distribution curves of defect density reported in other literatures (Slack et al., 2007), the first halves of the two distribution curves, which refer to landfills with defect densities less than 10/ha and construction qualities in the top 40%, exhibit a significant overlap, while the second half differs greatly. This means that in China, the distribution of initial defect density in the Top 40% landsites is similar to that in a developed country like the UK (Slack et al., 2007). However, the construction defect density in the last 60% of landfills is greater than those in China. This may be due to the fact that in these landfills, HDPE GMBs are installed by workers who have no professional training and have very little construction experience. On the contrary, developed countries such as the United Kingdom and the United States attach great importance to the quality control and assurance of the impermeable layer installation process, and the qualifications of HDPE GMB installation workers is strictly required, hence they must undergo a certain period of professional training before they can engage in relevant work.

The proportion of defects in different sizes on HDPE GMB is shown in Fig. 4. It is found that defects below 1 mm^2 accounted for 12% of total detected defects in 108 landfills. The defects of 1 mm^2 to 1 cm^2 are about 41%, so the small defects of less than 1 cm^2 are about 53%, which means more than half of the defects are smaller than 1 cm^2. Defects above 50 cm^2 account for 12%, this part of the defects is large defects, usually due to construction machinery tearing, weld cracking and other factors.

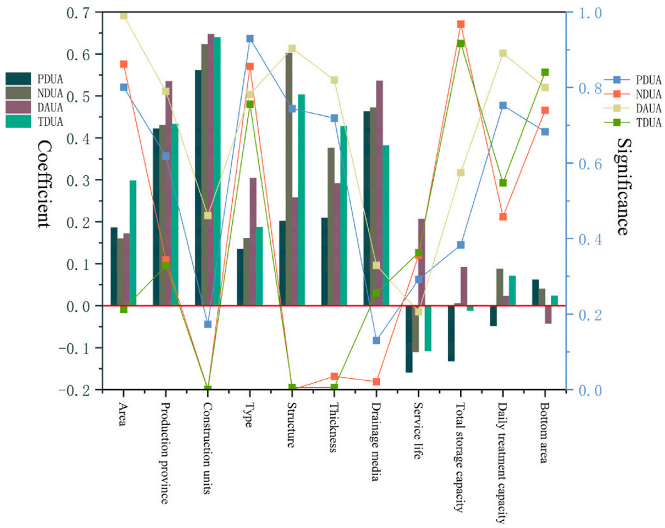
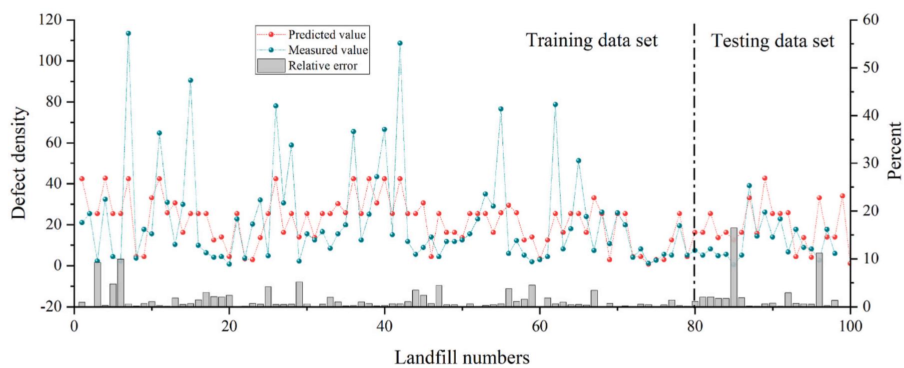


Fig. 5. The correlation analysis results of 11 indices with PDUA, NDUA, TDUA, and DAUA.

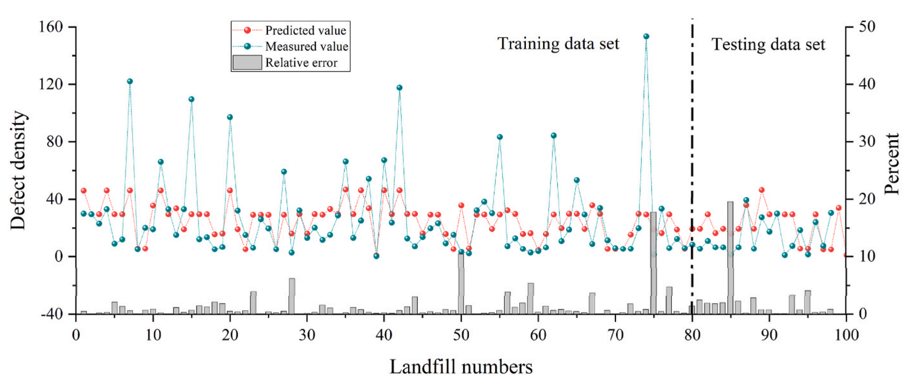
3.2. Main factors affecting initial defects

Fig. 5 shows the correlation analysis results of 11 indices with PDUA, NDUA, TDUA, and DAUA. The PDUA significant coefficients for continuous variables including landfill service life, total storage capacity, daily treatment capacity, and bottom area range from 0.29 to 0.75, while the PDUA significant coefficients for discontinuous variables containing landfill location, type, HDPE GMB production region, thickness, construction unit, drainage media and drainage system structure are between 0.17 and 0.93. All these significance coefficients are greater than 0.05, indicating that the 11 indices have no significant impact on PDUA. Regarding NDUA, the significant coefficients for continuous variables range from 0.36 to 0.97, indicating that continuous variables have no significant influence on NDUA. Among the discontinuous variables, the construction unit ($r = 0.623$, $p < 0.05$), drainage system structure ($r = 0.602$, $p < 0.05$), HDPE GMB thickness ($r = 0.376$, $p < 0.05$), and drainage media ($r = 0.472$, $p < 0.05$) have significant correlations with NDUA. A predictive model was constructed using these as independent variables.

Similarly, the significant results of DAUA and TDUA with continuous factors such as service life, total storage capacity, daily treatment capacity, and bottom area are 0.20–0.89 and 0.36 to 0.92, respectively, indicating that all four independent variables have no significant impact on DAUA and TDUA. Moreover, the results of the column correlation



(a) Comparison of non-pinhole defects in a unit area (NDUA) with measured value and prediction value



(b) Comparison of total defects in a unit area (TDUA) with measured value and prediction value

Fig. 6. Comparison of model prediction with measured value and prediction error.

Table 3
Prediction error statistics for non-pinhole and total defects.

Relative error	Non-pinhole defects		Total defects	
	Number	Proportion (%)	Number	Proportion (%)
$\lvert\varepsilon\rvert < 0.2$	17	17.3	13	13.5
$0.2 < \lvert\varepsilon\rvert < 0.5$	23	23.5	25	26.0
$0.5 < \lvert\varepsilon\rvert < 1$	23	23.5	23	24.0
$1 < \lvert\varepsilon\rvert < 2$	14	14.3	17	17.7
$2 < \lvert\varepsilon\rvert < 5$	16	16.3	13	13.5
$\lvert\varepsilon\rvert > 5$	5	5.1	5	5.2

analysis between DAUA and discontinuous variables including landfill location, type, HDPE GMB production region, thickness, construction unit, drainage media, and drainage system structure indicated that these discontinuous variables also have no significant influence on DAUA (significance coefficients range from 0.32 to 0.99). However, construction unit ($r = 0.64$, $p < 0.05$), drainage system structure ($r = 0.503$, $p < 0.05$), HDPE GMB thickness ($r = 0.428$, $p < 0.05$), and type of drainage media ($r = 0.412$, $p < 0.05$) are significantly correlated with TDUA and can be used as independent variables to construct a predictive model.

In conclusion, among the four corresponding indicators of HDPE GMB defects, PDUA and DAUA did not show a significant correlation with the 11 independent variables. However, there is a strong relationship between NDUA/TDUA and the construction unit, drainage system structure, HDPE GMB thickness, and the type of drainage media. That means the change in the number of HDPE GMB defects is caused by different construction units, as well as various drainage system structures, HDPE GMB thicknesses, and types of drainage media.

3.3. Quantitative prediction models for initial defects

A prediction model of NDUA and TDUA and their potential correlation factors was constructed through multiple regression analysis, as shown in formulas 4 and 5. The F value of Model is 6.6461 ($p < 0.05$), indicating that the model has statistical significance. Fig. 6 shows the comparison of the model predictions and measurements for the NDUA and TDUA, and the error statistics are presented in Table 3. From the statistical table of error distribution, for NDUA predictions, 64.30% had a relative error of ±1 or less, and only 5.10% had a prediction error of more than ±5. Samples with substantial errors were determined to be data with zero or unusually large measured values. In the TDUA model, 63.50% of the relative errors were within ±1, while 5.20% of the errors exceeded ±5. ND supplementation was determined to be the major source of substantial inaccuracies in the samples. The accuracy of the model for anticipating non-pinhole defect density and total defect density satisfies practical requirements.

$$NDUA = \begin{cases} 25.7 + 16.7 \times x_6 - 12.9 \times x_2 - 11.8 \times x_3, x_2 = 1 \\ 25.7 + 16.7 \times x_6 - 11.8 \times x_3 - 9.4 \times x_5, x_2 = 0 \end{cases}, \tag{4}$$

$$TDUA = \begin{cases} 16.1 + 17.2 \times x_6 - 14.0 \times x_2 + 12.9 \times x_3, x_2 = 1 \\ 16.1 + 17.2 \times x_6 + 12.9 \times x_3 - 10.7 \times x_5, x_2 = 0 \end{cases}. \tag{5}$$

Formula 4 indicates that the four discontinuous variables including the construction unit (x_6), the drainage system structure (x_2), the HDPE GMB thickness (x_3) and drainage media (x_5) all have a significant impact on NDUA. Specifically, in terms of the qualification of the construction unit (x_6), when the construction unit has neither professional anti-seepage construction qualifications nor professional engineering construction qualifications with quality management system certification, environmental management system certification, and occupational health and safety management System Certification, x_6 takes 1, and at this time, the NDUA increases by 16.7; when the construction unit is another engineering company, x_6 takes 0, and at this time, there is no impact on the NDUA value. This indicates that informal construction units can lead to a significant increase in NDUA. Regarding the structure

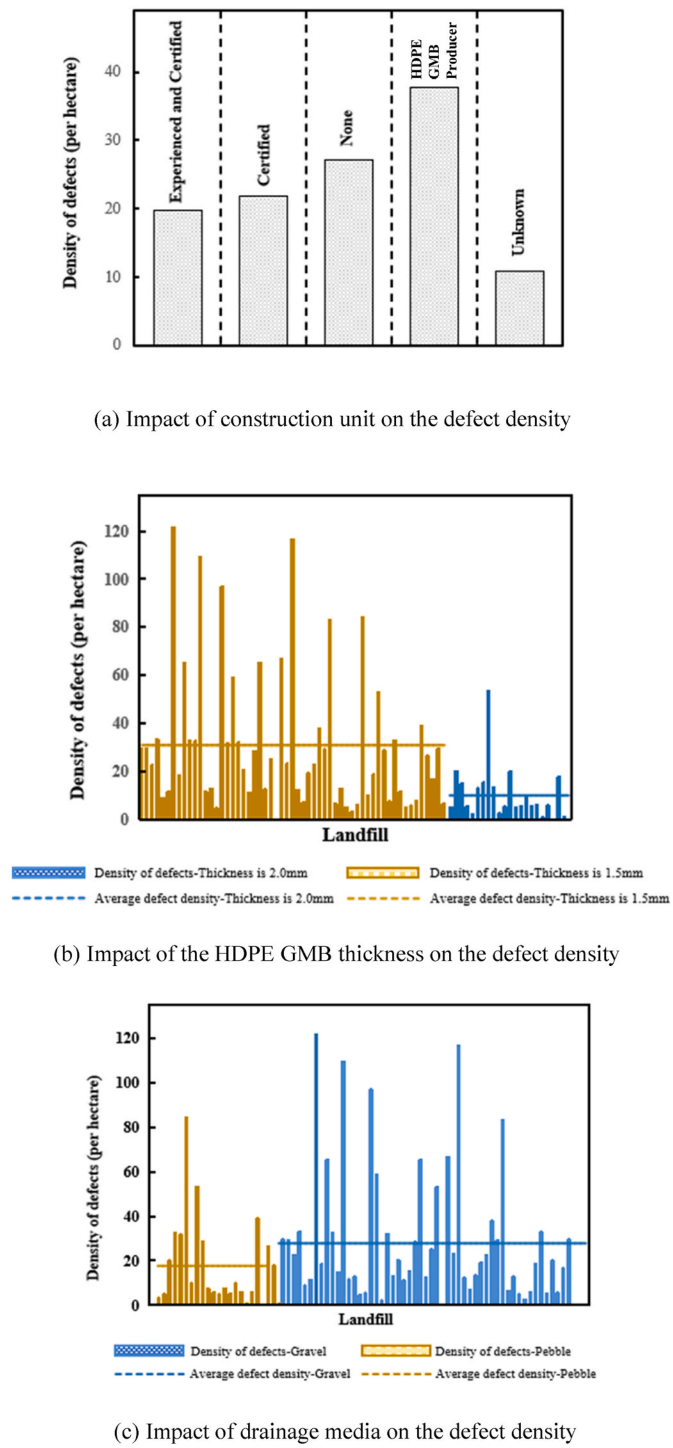


Fig. 7. Impact of key variables on the defect density.

of the drainage system (x_2), when no drainage particles are used in the drainage system or the number of protective layers between the drainage particles and the HDPE GMB is greater than 1, x_2 takes 1, and in this case, the NDUA decreases by 12.9; when the number of protective layers between the drainage particles and the HDPE GMB in the drainage system is less than or equal to 1, x_2 takes 0, and there is no impact on the NDUA value. This suggests that the structure of the drainage system has a direct influence on the generation of defects, and increasing the number of protective layers between the drainage particles and the HDPE GMB can effectively reduce the occurrence of defects. Concerning the thickness of the HDPE GMB (x_3), when its thickness is greater than or

Table 4
Comparison of damage before and after defect repair.

Number		Area (m^2)	Defect condition				Defects per 10,000 m^2			
			Manufacturing holes[a]	Installation holes[a]	Total defect area[a]	Total number of holes[a]	Manufacturing holes[a]	Installation holes[a]	Total defect area[a]	Total number of holes[a]
A	Before	9000	1	12	29	13	1.0	13.3	32.2	14.4
	After	9000	1	4	0.7	5	1.0	4.4	0.8	5.6
Reduction rate							0.0	0.7	0.98	0.6
B	Before	3000	18	4	16	22	60.0	13.3	53.3	73.3
	After	3000	1	2	0.6	3	3.3	6.7	2.0	10.0
Reduction rate							0.94	0.50	0.96	0.86

Note: [a]Area is in cm^2, and the number of holes is in pieces.

equal to 2 mm, x_3 takes 1, and at this time, the NDUA decreases by 11.8; when the thickness is less than 2 mm, x_3 takes 0, and there is no impact on the CDUA value. This shows that there is a direct relationship between the thickness of the HDPE GMB and NDUA, and increasing the thickness can effectively decrease the occurrence of defects. Regarding the type of drainage particles (x_5), when they are pebbles or no drainage particles are used in the drainage system, x_5 takes 1, and at this moment, the NDUA decreases by 9.4; when the drainage particles are gravels, x_5 takes 0, and there is no impact on the NDUA value. This indicates that using pebbles as the drainage medium has a positive effect on controlling the occurrence of defects. In conclusion, by choosing a regular construction company, setting up protective layers between the guiding medium and the HDPE GMB, selecting an HDPE GMB with a thickness greater than 2 mm, and using pebbles instead of sharp guiding medium like gravels, the defects can be reduced by 16.7, 12.9, 11.8, and 9.4/ha respectively.

Comparing Formula 5 with Formula 4, it is found that factors affecting NDUA are the same as those affecting TDUA, however, these factors have a greater impact on TDUA. Taking the guide medium as an example, the change from gravel to pebble reduces NDUA by 9.4 holes/hectares, while it reduces TDUA by 10.7 holes/hectares. Considering that TDUA comprises NDUA and PDUA, these factors might also have an effect on PDUA, but the effect is much smaller than that on NDUA. The model's prediction results were verified by detecting total defects in actual landfills. Fig. 7 demonstrates the influence of key variables such as the construction unit, HDPE GMB thickness, and drainage media on the defect density. It is observed that the average number of defects in 1.5 mm HDPE GMB is significantly higher than that in 2.0 mm HDPE GMB. Likewise, the HDPE GMB defect in the landfill using gravel as the guiding medium is also larger than that in the landfill using pebble as the guiding medium.

3.4. Quality assurance and initial defect correction factor

It has been the experience of the United States and Europe that the number of defects in landfill HDPE GMBs can be reduced by 90% with effective quality control during the construction of the landfill and quality assurance measures such as defect detection and defect repair after construction is completed (McQuade and Needham, 1999). However, early landfills in China lacked quality control measures, and some landfills implemented quality control measures but were unable to confirm the effectiveness of measures due to a lack of documented evidence. Therefore, this section focuses on the impact of quality assurance measures such as HDPE GMB integrity testing and defect repair on reducing the number of defects.

For this purpose, defect re-detection was performed in two landfills with integrity testing and completed defect repairs. The number of defects was compared before and after the re-detection, and the results are shown in Table 4. Table 4 presents the findings, according to which the damage situation has significantly improved, and the area of defect may be decreased to 1/50–1/25 of the initial state. In summary, the application of quality assurance and quality control can significantly reduce the number of defects generated. This is in agreement with investigations by the EPA which found that the number of defects in HDPE GMBs could reduce 90% after integrity testing and damage repair. Although landfills in China, the United States, and Europe have different initial defect characteristics, their quality control and assurance systems, integrity testing and defect repair measures, and defect reduction considerations are the same. It is reasonable and feasible to use 0.1 as a correction factor.

4. Implications

Based on the defect prediction model described above, it is possible to predict the generation and evolution of defects based on the detection data provided. During the construction of the prediction model, it was found that construction unit qualification and HDPE GMB thickness, the type of drainage media, and the drainage system structure were key influencing factors for installation defects and total defect generation. According to the relevant national standards, HDPE GMBs with a thickness greater than 2 mm should be selected for laying, and a highly qualified construction unit should perform the installation. In addition, pebbles should be used instead of gravel as the drainage media, and a geotextile protective layer should be added between the drainage media and the HDPE GMB. The above measures can significantly reduce the generation of defects in the HDPE GMB laying process and fit in well with the logic of most landfill designs and operations.

Before a landfill is taken into service, a further assessment of whether the landfill meets the operational criteria for being ready for use is performed by conducting defect detection after the original defects have been repaired. This is a quality assurance assessment approach. A correction factor for the assessment model has been determined to suit China's landfill defect repair methods for the wider application of the model.

The findings of this study provide data on the number and area of defects in Chinese landfills and the practical application of the prediction models, with a strong link between the two. This will offer a future research direction for the identification and evolution of defects in landfills under non-operational conditions, as well as the measures that can be taken by management to prevent the spread of contamination based on the evolutionary patterns of landfill defects.

5. Conclusions

1. The defect density of 108 landfills ranged from 0 to 39 defects/ha, with an average of 15 defects/ha. The defect area ranged from 0 to 1228 cm^2 per hectare, with an average value of 122 cm^2 per hectare.

2. Of the 11 pre-identified factors, four were demonstrated to be significantly related to defect density, namely, construction unit qualification, the HDPE GMB thickness, the type of drainage media, and the drainage system structure.
3. The four-parameter statistical model for initial defect prediction constructed in this paper can reasonably predict the initial defect occurrence. Samples in which the relative errors of the predicted number of construction defects and total defects were less than 1 accounted for 64.3% and 63.5% of the total samples, respectively.
4. Based on the established initial defect prediction model, it can offer methodological support for landfill performance assessment, landfill environmental impact assessment.

CRediT authorship contribution statement

Feng Yang: Methodology, Conceptualization. **Jingcai Liu:** Investigation. **Ting Lin:** Methodology, Investigation. **Changxin Nai:** Project administration, Methodology. **Yuqiang Liu:** Supervision, Funding acquisition. **Panpan Qiu:** Investigation, Data curation. **Ya Xu:** Writing – original draft, Funding acquisition. **Can Qian:** Writing – review & editing.

Acknowledgments

This work was supported by the Joint Research Program for ecological conservation and high-quality development of the Yellow River Basin (grant number 2022YRUC010303) and the National Key Research and Development Program of China (grant number 2023YFC3708902).

Data availability

No data was used for the research described in the article.

References

Amano, K.O.A., et al., 2020. Effect of waste landfill site on surface and ground water drinking quality. Water Environ. J. 35, 2.
Barakat, F., et al., 2024. Transport parameters for PFOA and PFOS migration through GCL's and composite liners used in landfills. Geotext. Geomembranes 52, 762–772.
Drury, D., et al., 2003. The Development of LandSim 2.5. Solihull. Environment Agency. Olton Solihull.
EPA, 1989. EPA625/489/022 Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Center for Environmental Research Information Office of Research and Development, Cincinnati.
Eurostat, 2019. Municipal waste statistics - statistics explained [online] Available at https://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics#Municipal_waste_treatment. (Accessed 10 November 2019).
Guan, S.P., et al., 2010. Affecting factors of electrical leakage detection method for double-liner landfill. Environ. Sci. Technol. 33, 113–115.
Kjeldsen, P., Christensen, T.H., et al., 2002. Present and long-term composition of msw landfill leachate: a review. Crit. Rev. Environ. Control 32, 297–336.
Lentz, J.J., 1981. Apportionment of net recharge in landfill covering layer into separate components of vertical leakage and horizontal seepage. Water Resour. Res. 17, 1231–1234.
McQuade, S.J., Needham, A.D., 1999. Geomembrane liner defects—causes, frequency and avoidance. Geotech. Eng. 137, 1353–2618.
Mohammad, M.A.K., et al., 2017. Distribution of trace elements in groundwater around beris lalang landfill bachok, kelantan, Malaysia. Asian J. Water Environ. Pollut. 14, 41–50.
Morita, A.K.M., et al., 2021. Pollution threat to water and soil quality by dumpsites and non-sanitary landfills in Brazil: a review. Waste Manag. 131, 163–176.
Nai, C.X., et al., 2005. Research on geomembrane leakage detection system. Environ. Sci. Technol. 28, 1–3.
Nai, C.X., et al., 2006. The method of leakage location in geomembrane liner. Res. Environ. Sci. 19, 64–66.
Naveen, B.P., et al., 2018. A study on contamination of ground and surface water bodies by leachate leakage from a landfill in Bangalore, India. Int. J. Geo-Eng. 9, 27–46.
Nie, Z.Y., et al., 2021. Drivers and ecological consequences of arsenite detoxification in aged semi-aerobic landfill. J. Hazard Mater. 420, 126597.
Rowe, R.K., 2018. Geosynthetic clay liners: perceptions and misconceptions. In: 11thInternational Conference on Geosynthetics. Seoul, Korea, September.
Saeedreza, H., et al., 2017. Remediation of groundwater contaminated with arsenic through enhanced natural attenuation: batch and column studies. Water Res. 122, 545–556.
Sekhohola-Dlamini, L., Tekere, M., 2020. Microbiology of municipal solid waste landfills: a review of microbial dynamics and ecological influences in waste bioprocessing. Biodegradation 31, 1–21.
Slack, R.J., et al., 2007. Household hazardous waste disposal to landfill: using LandSim to model leachate migration. Environ. Pollut. 146 (2), 501–509, 2007.
Sun, W., et al., 2019. Evaluation of optimal model parameters for prediction of methane generation from selected U.S. landfills. Waste Manag. 91, 120–127.
Sun, X.C., et al., 2019. Evolution of geomembrane degradation and defects in a landfill: impacts on long-term leachate leakage and groundwater quality. J. Clean. Prod. 224, 335–345.
Wang, X.F., et al., 2024. Modeling risk assessment of soil heavy metal pollution using partial least squares and fuzzy logic: a case study of a gully type coal-based solid waste dumpsite. Environ. Pollut. 352, 124147.
Xiang, R., et al., 2020. Aging behaviors of HDPE geomembrane in landfill environment and its impact on pollution risk of surrounding groundwater. Res. Environ. Sci. 33, 978–986.
Xu, Y., et al., 2014. Pollution risk assessment of long-term leaking in landfill-based on the Landsim model. China Environ. Sci. 34, 1355–1360.
Xu, Y., et al., 2015. Statistical analysis on the density of accidental-hole in landfill liner system. Chin. J. Environ. Eng. 9, 4558–4564.
Xu, Y., et al., 2019. Buffering distance between hazardous waste landfill and water supply wells in a shallow aquifer. J. Clean. Prod. 211.
Xue, Q., et al., 2006. Study on risk prediction of landfill leachate leakage pollution. J. Basic Sci. Eng. 14, 199–204.