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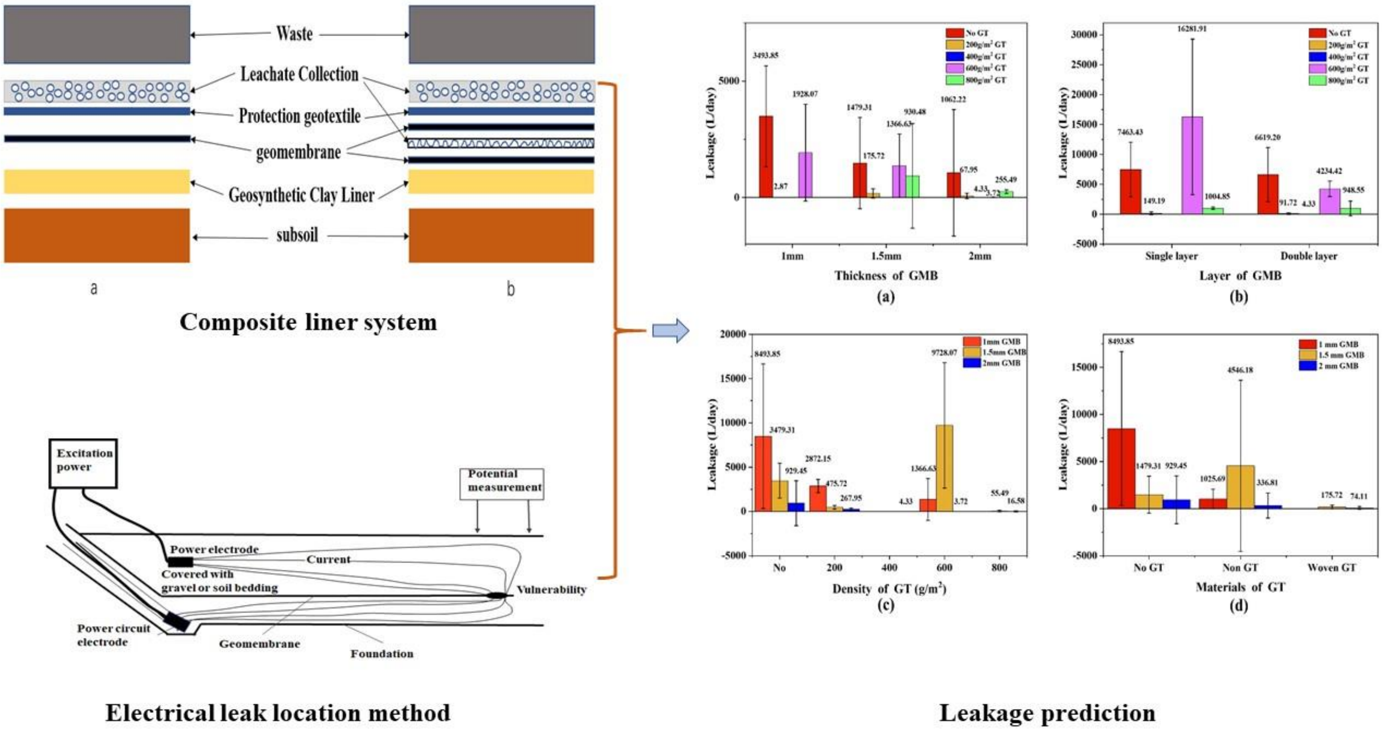
Graphical Abstract



Geomembrane leaks detection and leakage correlation factor analysis of composite liner systems for fifty-five (55) solid waste landfills in China

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Abstract:

In composite liner system (CLS), there are little field data on the number, size, and shape of geomembrane (GMB) holes, which are the key parameters to identify and evaluate the volume of leachate leakage from landfills. In this paper, in-situ detection of GMB holes in composite liner systems of 55 solid waste landfills in China was conducted by electrical leak location (ELL) method, and the following conclusions were drawn. The holes frequency, equivalent radius, and theoretical leakage volume of double-layer systems are lower than those of single-layer systems under the same geotextile (GT) density by 28.2%, 51.4%, and more than 60%, respectively. As the thickness of GMB increases, the holes frequency, equivalent radius and theoretical leakage volume reduce observably. Regarding protecting GMB, the density of geotextiles should not be less than 600 g/m^2. Through the analysis of various correlation factors, the thickness of geomembrane is an important parameter affecting the amount of leakage. This study will provide a reference for analyzing the data of field investigation, which would provide constructive suggestions for the composite liner system.

Keywords: Solid waste landfill; Composite liner system; Geomembrane; Leak detection; Field survey; Leakage

1. Introduction

To control the migration of leachate contaminants to underlying soil and groundwater around landfills, Chinese National Standards necessitate a composite liner system being constructed at the bottom of landfills to prevent landfill leachate from leaking and polluting the environment. Composite liner systems are widely used in landfill containment systems because of their excellent barrier properties against organic and inorganic contaminants (Lupo et al., 2007; Touze et al., 2021). The composite liner system mainly consists of high-density polyethylene (HDPE) geomembrane (GMB), geosynthetic clay liners (GCL) or compacted clay liner (CCL), nonwoven fabric, geosynthetic drainage mats, and other multilayer structures. The structural integrity of the GMB, which serves as the primary barrier layer of the composite liner system, determines the impermeability and barrier performance of the composite liner system (Cornwall et al., 2020). However, GMB holes are often unavoidable due to welding defects, construction machinery crushing, hard material puncture, nonuniform foundation settlement, leachate corrosion aging. Unlike GCL and CCL (Rowe et al., 2016), the holes in GMB cannot self-heal, which provides a direct pathway for leachate seepage contamination.

Even in well-designed and constructed facilities, geomembrane holes cannot be prevented during landfill construction, so the process of geomembrane hole detection and the assessment of the amount of leakage from the composite liner system will become essential. Both of these factors have been investigated from various perspectives.

As the leakage detection technology for composite liner systems continues to evolve, the accuracy of the detection results continues to improve. In recent years, the researches on leakage detection methods for composite liner systems have received more and more attention. The current landfill leakage detection methods mainly fall into two categories, one is for the landfill operation stage, and the primary technical method used is the high-density resistivity detection method. However, the research in question is still being tested in laboratory models. Binley et al. (2003) compared two electrode geometries under a series of controlled electrical leakage experiments and demonstrated how the two configurations could detect and locate leaks in GMB. Ping et al. (2005) developed a high-voltage direct current (DC) method by loophole current model for landfill leak detection, which solves the problems of a large amount of collected data and a long transmission distance due to the large detection area of the landfill. Due to the non-homogeneity of solid waste landfills, which seriously affects the feasibility of leakage detection in the operation phase of landfills, few cases of field detection of results have been reported. The second category focuses on the landfill construction phase. After the bottom composite liner system has been completed, a series of electrical leak location methods are used to detect the GMB holes in the composite liner system. Xiao et al. (2015) experimentally investigated the role of the dipole method in leachate leakage detection, including the leakage size of the leachate, the laminar structure of the leachate drainage layer, and the water intrusion into the leachate. Since 2016, the Chinese government has promulgated the Technical Specification for Leak Location Surveys of GMBs in Municipal Solid Waste Landfill (2016) (CJJT 214-2016), which the authors of this paper edited. The specification requires that new solid waste landfills be tested for the integrity of GMB.

The amount of leakage caused by leachate passing through a geomembrane is highly valued as a vital parameter indicator to evaluate the service performance of landfill composite liner systems. On the theoretical side, many researchers have tried to obtain an accurate solution for the amount of leakage through geomembranes, which improves the accuracy of calculating the amount of leakage. J.P. Giroud et al. (1992) derived a set of formulas where the GMB is placed on a layer of low-permeability soil to form a composite liner. Rowe (2000) proposed a semi-analytical solution formula for calculating leakage through circular GMB holes, and the expression can be widely used in practical problems. Based on the HCA method, Zhan et al. (2014) have developed a method for predicting leakage volume under complex conditions where holes exist around wrinkles. Yan et al. (2021) proposed an analytical solution for the non-isothermal diffusion of organic compounds in unsaturated GMB/CCL composite liners. The study explores how the thermal gradient and unsaturated water distribution affect the dispersion of pollutants, which could obtain the law of contaminant migration under coupled thermo-hydraulic conditions.

Rowe et al. (2021a) conducted laboratory tests through roadbeds and proposed an empirical formula to predict leakage from circular GMB holes in tailings pond applications. Fan et al. (2021b) measured leakage through laboratory tests and showed that changing the hole shape from circular to noncircular increased leakage. Cen et al. (2022) conducted a series of puncture tests to investigate the puncture behavior of defective GMBs with different types of defects, including cracks, scratches, and circular holes, which provides an excellent benchmark for the practical design of protective layers. Li et al. (2021) investigated the effects of different exposure environments on the HDPE GMB lifespan at the antioxidant depletion stage, which provides a reliable methodological basis for the risk control and life prediction of HDPE GMBs. Chou et al. (2018) investigated the potential for piping erosion of tailings through a 1-cm diameter GMB defect in a series of physical experiments. They found that a critical stress condition would affect the leakage.

From the above findings, we found that GMB hole parameters, such as hole frequency, pore size and geometry, and composite liner system structure are key parameters affecting the amount of geomembrane breakage leakage. However, there needs to be more in-situ field survey data on the damage of GMBs of CLSs for solid waste landfills. In this paper, the authors analyze the data from 55 landfills in China, and the conclusions obtained will provide a reliable reference for landfill construction design and operation and maintenance.

The two objectives of this study are (i) to statistically analyze the number and causes of GMB holes in composite liner systems and the correlation with the structural form of composite liner systems to provide a parameter basis for the design and safe construction of composite liner systems in landfills, and (ii) to provide a statistical analysis of the number, size, and shape of holes in GMB with different structural forms and to solve the problem of lack of key parameters for calculating the volume of leakage in existing landfill sites.

2. Materials and Methods

2.1 Detection object

Composite liner systems play a critical role in landfills by preventing leachate from penetrating the landfill, thereby reducing the contamination of groundwater sources. Different types of landfills are required to have a CLS, with one layer of geomembrane usually laid in the design configuration of domestic waste landfills and general solid waste landfills and two layers of geomembrane usually laid in domestic waste incineration fly ash landfills and hazardous waste landfills. A schematic diagram of the composite liner system is shown in Figure 1, with (a) a single-layer composite liner structure and (b) a double-layer composite liner structure.

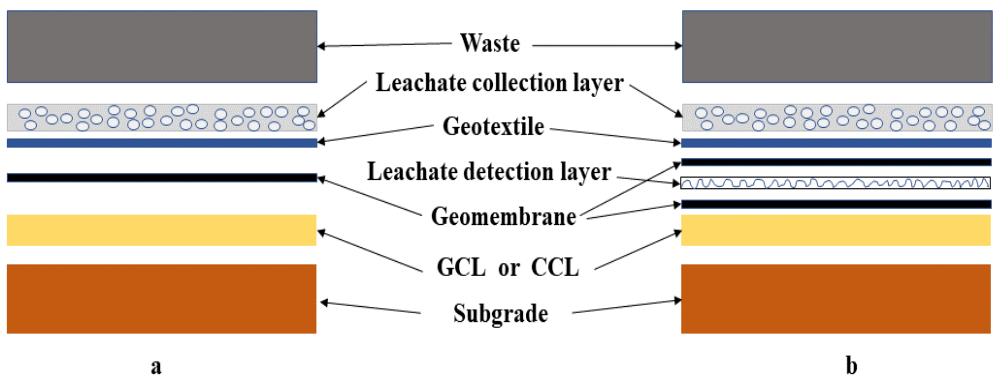
In this study, the GMB integrity of the CLS was detected for fifty-five solid waste landfills in China, and the information on GMB holes detected in the composite liner system was counted. Twenty-six domestic waste landfills, thirteen general solid waste landfills, ten domestic waste incineration fly ash landfills, and six hazardous waste landfills were included in the fifty-five landfills. The information of the detected holes is counted along with the information of the landfill to which they belong, including the province where the landfill is located, the type of landfill, the area of the landfill detected, the type, thickness, and the number of layers of the GMB in the composite liner system, and the material and mass density of the GT. By analyzing the parameters of the holes, the influence of the structure of the composite liner system on causing GMB holes can be explored so that the design of the composite liner system of the landfill can be optimized. Some of the landfill information counted is presented in Table 1.

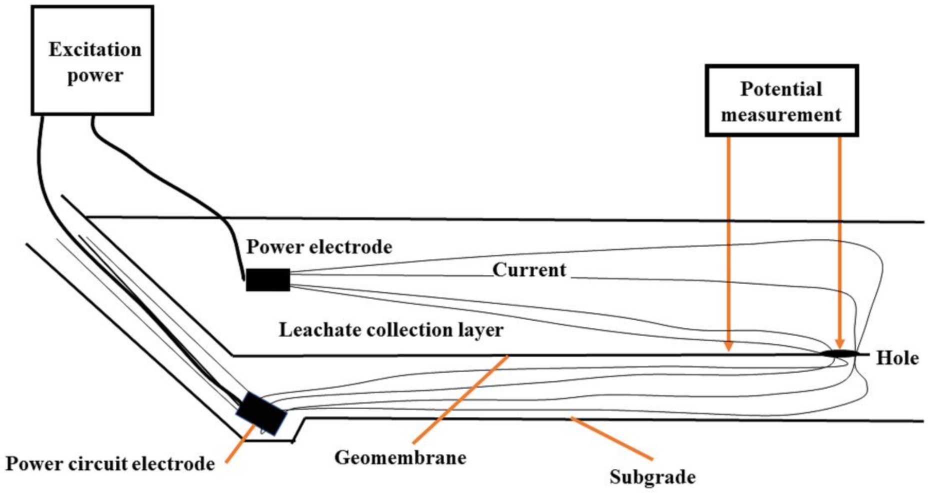
Table 1. Landfill type and hole rate statistics.

No.	Province	Landfill type	Detection area（ha）	Number of holes	GMB thickness （mm）	GMB layers	Geotextile density （g/m^2）	CQA
1	Hebei	FA	10000	4	2	2	200	Y
2	Shandong	DW	13000	0	2	1	UC	Y
3	Beijing	DW	51250	29	2	2	600	Y
4	Neimenggu	GSW	10200	1	2	2	UC	Y
5	Anhui	DW	29000	5	2	1	200	Y
6	Jiangxi	DW	31700	11	1.5	1	600	Y
7	Henan	DW	21000	77	1.5	1	200	N
8	Hubei	HW	50000	35	2	2	200	N
9	Neimenggu	HW	20000	1	1	2	200	Y
10	Sichuan	DW	240000	40	2	2	800	Y
11	Zhejiang	DW	12000	11	1	1	No	Y
12	Guangdong	DW	10000	5	2	2	200	Y
13	Gansu	DW	10000	2	1.5	2	600	Y
14	Guangdong	DW	80000	4	2	2	600	Y
15	Guizhou	GSW	16600	14	1	1	No	Y
16	Guangdong	DW	10000	1	1.5	2	600	Y
17	Jiangsu	DW	10000	5	1.5	1	UC	Y
18	Hunan	DW	58000	21	1.5	1	200	Y
19	Shanxi	GSW	12672	5	2	2	600	Y
20	Jiangsu	DW	23000	1	2	2	600	Y
21	Shandong	FA	12000	0	2	2	200	Y
22	Shandong	HW	13200	15	2	2	600	Y
23	Shandong	FA	10000	11	1.5	2	200	Y
24	Shandong	GSW	3500	10	1	2	UC	Y
25	Shandong	GSW	16390	4	2	2	300	Y
26	Liaoning	GSW	16000	0	2	1	UC	Y
27	Jilin	DW	34000	3	2	1	UC	Y
28	Hunan	HW	14000	0	2	2	800	Y
29	Guangdong	DW	60832	3	1.5	2	800	Y
30	Jiangsu	FA	50428	9	2	1	800	Y
31	Hebei	HW	9000	0	2	2	800	Y
32	Hainan	FA	10415	0	2	2	600	Y
33	Hainan	FA	35040	2	2	2	600	Y
34	Neimenggu	HW	13500	0	2	1	UC	Y
35	Jiangxi	FA	31000	2	2	1	600	Y
36	Guangdong	DW	18000	0	1.5	1	400	Y
37	Ningxia	DW	43000	16	2	2	600	Y
38	Henan	DW	10000	7	1.5	1	UC	Y
39	Neimenggu	GSW	13000	18	1	1	No	Y
40	Guangdong	GSW	168000	36	1	2	600	Y

41	Guangdong	FA	45000	2	1	2	600	Y
42	Guizhou	DW	8000	3	1.5	1	600	Y
43	Yunnan	DW	10000	3	1.5	1	UC	Y
44	Yunnan	GSW	10000	1	2	2	UC	Y
45	Guangxi	DW	10000	1	2	2	UC	Y
46	Fujian	DW	37000	4	2	2	200	Y
47	Zhejiang	DW	10000	4	1.5	1	UC	Y
48	Jiangsu	GSW	10000	1	2	2	200	Y
49	Guizhou	GSW	100000	113	1	1	No	N
50	Jiangsu	GSW	5577.25	4	1.5	2	200	Y
51	Jiangsu	GSW	10000	0	1.5	1	800	Y
52	Zhejiang	FA	2393.75	0	2	1	UC	Y
53	Guangdong	DW	91269	8	2	2	800	Y
54	Guangdong	FA	45000	2	1	2	600	Y
55	Chongqing	DW	38248.9	3	1.5	2	600	Y

Note:(1) FA = fly ash, DW = domestic waste, GSW = general solid waste, and HW = hazardous waste; (2) Most detection areas are approximated by integers; (3) “UC” represented “unclear”, “No” represented “No GT”; (4) “Y” represents that landfill has the good CQA, “N” represents that landfill has the poor or non-existent CQA.





c

Figure 1. Principle diagram of (a) structure of single-layer liner system, (b) structure of double -layer liner system, (c) leakage detection by dipole method.

2.2 Detection method

The dipole method is a typical detection approach after landfill liner construction. The method has the advantages of low cost and high efficiency and has been widely used in detecting geomembrane integrity as technology continues to improve. Double electrode method of detection in the impermeable HDPE geomembrane above and below the media, each put a power supply electrode, a negative electrode buried under the geomembrane, a positive electrode placed on the HDPE geomembrane, electrode external excitation power. In compliance with the standard (2016) (CJJT 214-2016), the negative electrode buried below can be in two ways. One is to bury the negative electrode from the edge of the site under the geomembrane, and the other is to manually dig holes in the geomembrane first, bury the negative electrode through the holes, and then repair the manually dug holes after the testing is completed. When the HDPE geomembrane is intact, there is no current flowing in the power supply circuit; when there are loopholes in the HDPE geomembrane, current will be generated in the circuit, and a stable current field will be formed in the medium above and below the membrane, and the holes will be located according to the distribution law of the potential in the medium. The technical principle diagram is shown in Figure 1(c). It is worth noting that for the hole detection process of a double-layer system, the negative electrode is placed between the upper and lower geomembranes (i.e., leachate detection layer in Figure 1(b)), and the drainage mesh mat of the two layers is filled with conductive liquid in advance. Hence, the integrity detection result of geomembrane is for the upper geomembrane. The equipment used for the detection is mainly a power converter, potential meter, buried electrodes, and wires. The main parameters of the equipment are listed in Table 2.

Table 2. Main technical parameters of dipole detection equipment

Main technology	Parameter
Input voltage	AC 220
Output voltage	DC 0~1000V
Detection voltage	DC 0~1000V
Dipole separation distance	According to the field test

2.3 Analytical method

When the entire reservoir area is inspected, the suspected GMB holes are excavated above the composite liner to guide the drainage layer of stones. Then, the size of the broken hole is measured, and the broken hole place is repaired.

In this paper, three main analytical methods are used based on the results of GMB integrity detection and hole measurements of fifty-five landfill composite liner systems:

(1) A statistical analysis of the number and causes of GMB holes in composite liner systems and their correlation with the structural form of composite liner systems.

(2) A statistical analysis of the number, size, and shape of broken GMB holes of different structural forms of composite liner systems.

(3) The current barrier performance of composite liner systems of different structural forms is evaluated based on the relationship between the number, size, and shape of broken GMB holes of composite liner systems and the leakage volume.

2.3.1 Leakage calculation estimation

In order to study the leakage resistance of composite liner systems, it is essential to calculate the theoretical leakage of leachate for pore parameter analysis. In many field studies (Gilson-Beck, 2019), the results have demonstrated that the Rowe equation should be used instead of the Giroud equation to avoid seriously underestimating the leakage volume. Rowe (2000) proposed the Rowe-Booker equation for predicting leakage from a single hole:

$$Q = \{4 + [2.455 + 0.685 \tanh(0.6 \ln(r_0/T))\, r_0/T]\} r_0 k_2 h_2 \quad (1)$$

where Q = leakage volume; r_0 = equivalent radius of the hole; k_2 = permeability coefficient of the tailings overlying the GMB; T = thickness of the tailings overlying the GMB; and h_2 = head loss above the hole.

In the Rowe-Booker equation, it is pointed out that when r/h tends to 0, the leakage volume depends on r_0. While when h/r_0 tends to 0, the leakage volume depends on ${r_0}^2$. Therefore, the leakage volume will increase rapidly when the radius of the hole grows from small to large. The r_0 is mentioned above that represents the equivalent radius.

The shape of the holes is also one of the key parameters affecting the leakage volume. Exploring the holes leakage with different kinds of geometry in experiment, Rowe et al. (2021a) concluded expressions on shape factor Λ in terms of circular hole and quasi-circular hole (e.g., square, diamond, rectangular and triangular-shaped holes). The shape factor Λ is 1 for circular holes, 1.15 for square, diamond, and triangular holes, and 1.13~1.33 for rectangular holes. Therefore, if the holes have an equal area with other conditions maintained, the rectangular holes have the most leakage, followed by square, diamond, and triangular holes, and the circular holes have the least leakage. Due to the effect of hole geometries on the leakage, the Rowe-Booker formula is modified as:

$$Q = \Lambda \Omega \xi H / (\Omega + \xi) \tag{2}$$

Where $\Omega = \{4 + [2.455 + 0.685 \tanh(0.6 \ln(r_0/T))\, r_0/T]\} r_0 k_2$; $\xi = \pi {r_0}^2 k_1 / t$; and H = total water heads above the holes, assuming that all holes are 0.3 m above in the analysis. To obtain a more accurate solution, the slit with a small B/L (B represented rectangular hole width, L represented rectangular hole length) was paid more attentions, which would be able to provide a method for estimating the hole leakage of knife slices (Rowe et al., 2022). Equation (3) provides a general solution for slit defect:

$$Q = kLH\eta \tag{3}$$

Where L is the length of slit defect, H is the total head loss, η is the dimensionless leakage factor which related to B/L, L/T and B/t. The daily flow rate of all holes in each landfill was averaged to represent the leakage level of the landfill (i.e., leakage is obtained by dividing total estimated leakage by aera).

2.3.2 Analysis of factors affecting leakage volume

After the hole parameters were counted, the factors influencing the leakage volume were investigated. Based on the statistical results, it was clearly found that the hole frequency, the thickness of the geomembrane, the number of layers of the geomembrane, the density of the geotextile, and the equivalent radius of the hole all affect the leakage volume results. The Pearson correlation coefficient is introduced, and the obtained parameters are substituted as samples into equation (4):

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (4)$$

Where r denotes the correlation coefficient, and X_i and Y_i denote the samples, and $\bar{X}$ and $\bar{Y}$ denote the expectation of X and Y, respectively.

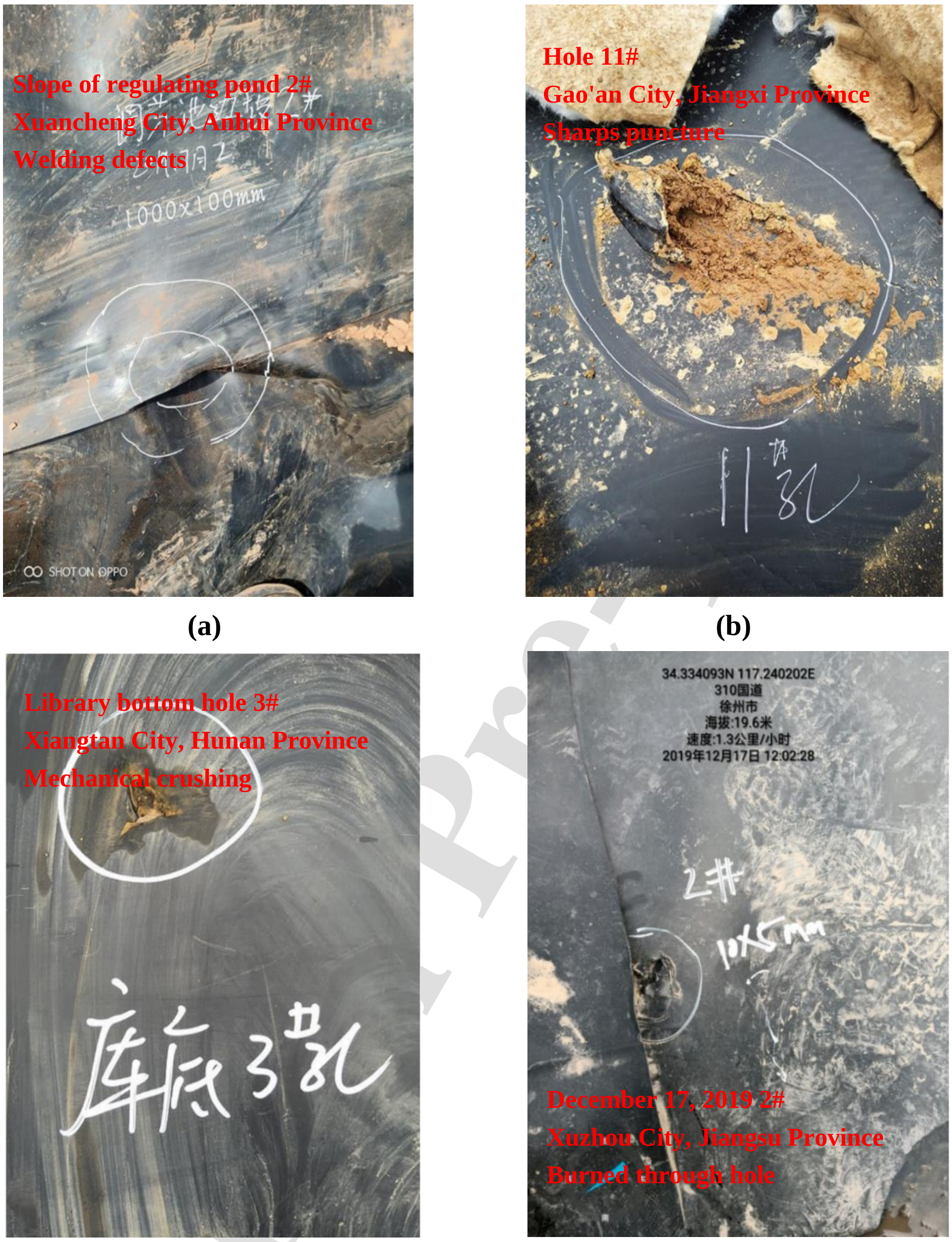
The Pearson correlation coefficient was introduced because it was necessary to de-quantize it to eliminate the effect of numerical magnitude differences, considering the sizeable numerical magnitude differences between the different parameters in this dataset. Dividing the respective standard deviation by the covariance eliminates the units and makes the calculated values between -1 and 1. Values 1 and -1 mean strong positive and negative correlations, respectively.

3. Results and Analysis

3.1 Geomembrane holes detection results and analyses

3.1.1 The geometry and cause of GMB holes

GMB holes have many forms, and their corresponding causes are attributed to different factors. Generally, the composite liner system in landfills is constructed from top to bottom using a drainage layer, geotextile, HDPE GMB, and GCL/CCL. As a result, the factors affecting the HDPE GMB holes should be considered in conjunction with the design of the composite liner system. Among all 557 holes that were statistically analyzed, there are four primary forms of holes, namely, sharps puncture, seam defects, mechanical crushing, and burned-through holes, accounting for 31.06%, 9.87%, 58.71%, and 0.18% of the total, respectively. It can be easily seen from the photos taken at the site (shown in Figure 2) that the geometrical shapes of the different holes forms are inconsistent, which also reflects external factors that can affect the formation of holes and will further affect the leakage volume in each hole. The welding with poor quality on HDPE GMB usually causes seam defects before the composite liner is laid in the landfill, resulting in subsequent leachate leakage. Most of the seam defects mainly exist between two adjacent HDPE GMBs, primarily rectangular. Burned-through holes occur when a hot-melt gun is used to melt HDPE GMB during welding or other working conditions, which generally has a small probability of occurrence, little data to analyze, and needs more rationality and necessity. Mechanical crushing is the cracking of the HDPE GMB by external machinery when laying composite liner systems in landfills. Sharps puncture occurs when a sharp object hooks and scratches the HDPE GMB, resulting in holes of various shapes and no direct regularity in the size of the area.



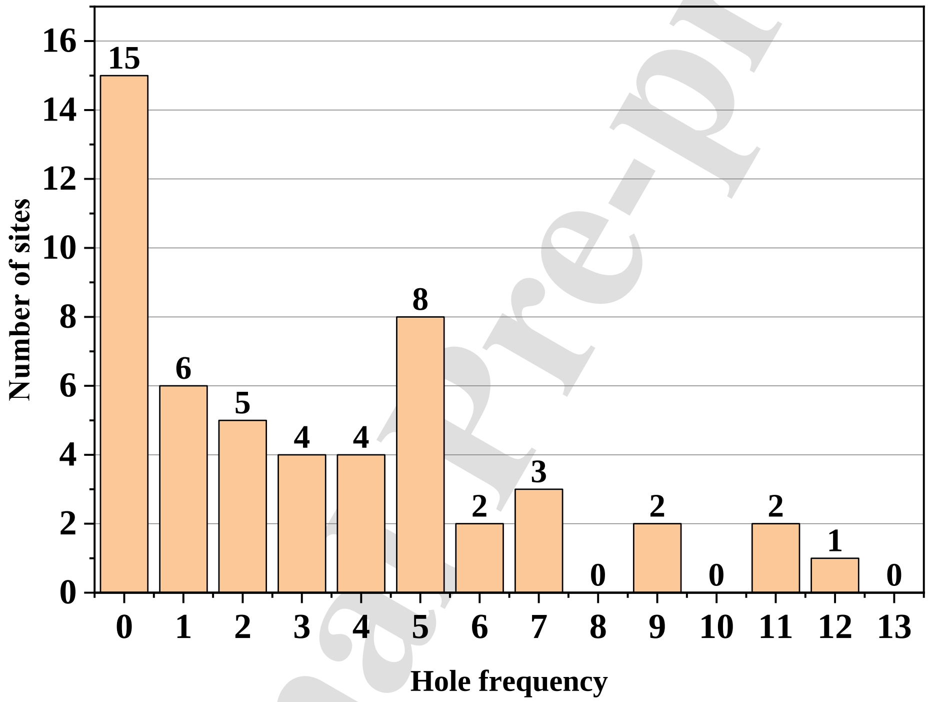
(a) (b) (c) (d)

Figure 2. On-site photos of holes in HDPE GMB: (a) Seam defects, (b) Sharps puncture, (c) Mechanical crushing, (d) Burned-through hole

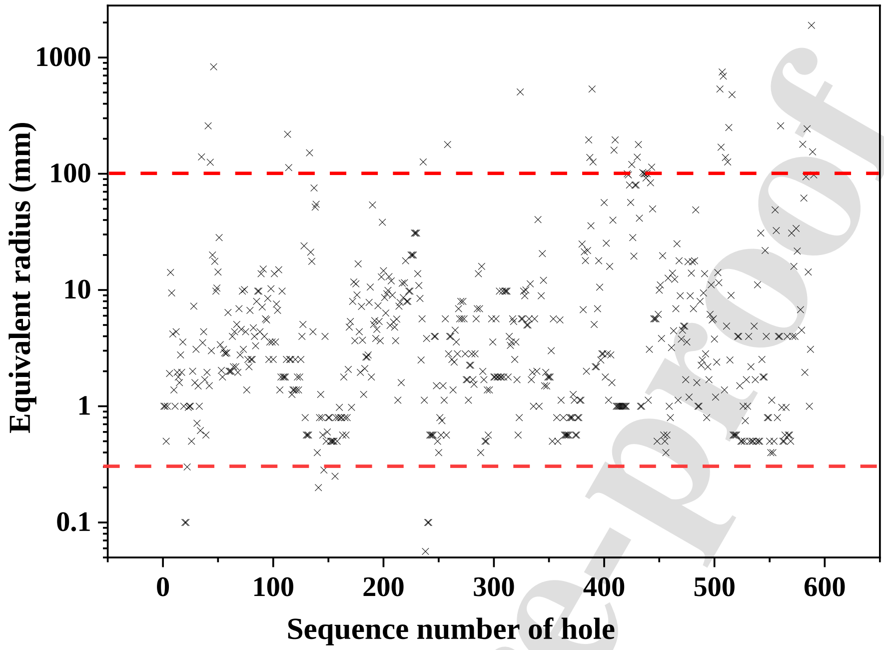
3.1.2 Analysis of geomembrane holes parameters

The fundamental parameters of all holes were analyzed statistically to understand further the basic profile of the holes investigated on-site and to facilitate the subsequent leakage analysis. The main statistics were the type of landfill, site area, material and quality of the geotextile, number of layers and thickness of the HDPE GMB, and the number, area, and shape of the individual site holes.

The hole frequency (i.e., the number of holes per hectare) was calculated and plotted, as shown in Figure 3(a), based on the number of holes and the entire landfill reservoir area probed. The figure shows that the average hole frequency of the 55 landfill GMB is 4.16, with porosity in the 0–4 and 5–11 intervals of hole frequency occupying 80% and 20%, respectively, which agrees with the discrete distribution of the data. Among the landfills investigated by Gilson-Beck (Gilson-Beck, 2019), the hole frequency was mainly concentrated between 0 and 1.25, with an average hole frequency of 0.27 for the 50 landfills, significantly lower than the average hole frequency of landfills in China. The data sets collected from the fifty projects with HDPE GMB and on-site CQA in North America are analyzed in multiple effects, including ELL Method, CQA, and GMB properties. The influence of GMB properties would not be the main factor causing the differences due to the exact specified materials (i.e., HDPE) in the CJJ 113-2007 code. The distinctions in the investigation of landfill ELL methods between the Gilson-Beck and authors are that the different kinds of ELL methods (e.g., water puddle, arc testing, soil dipole) depend on liner system conditions in North America. At the same time, the same ELL Method is adopted in 55 landfills in China. Geological condition is a considerable element in the process of detecting 55 landfills. The dipole methods are applied to the side slope and subgrade. Too many studies reveal the significance of CQA (Forget et al., 2005; Grace et al., 2000). The listed statistics in Gilson-Beck's paper are outright offered with construction quality assurance in place, whereas some in China are not. The hole frequency for landfills where less strict CQA is performed is much higher than those with poor or non-existent CQA.

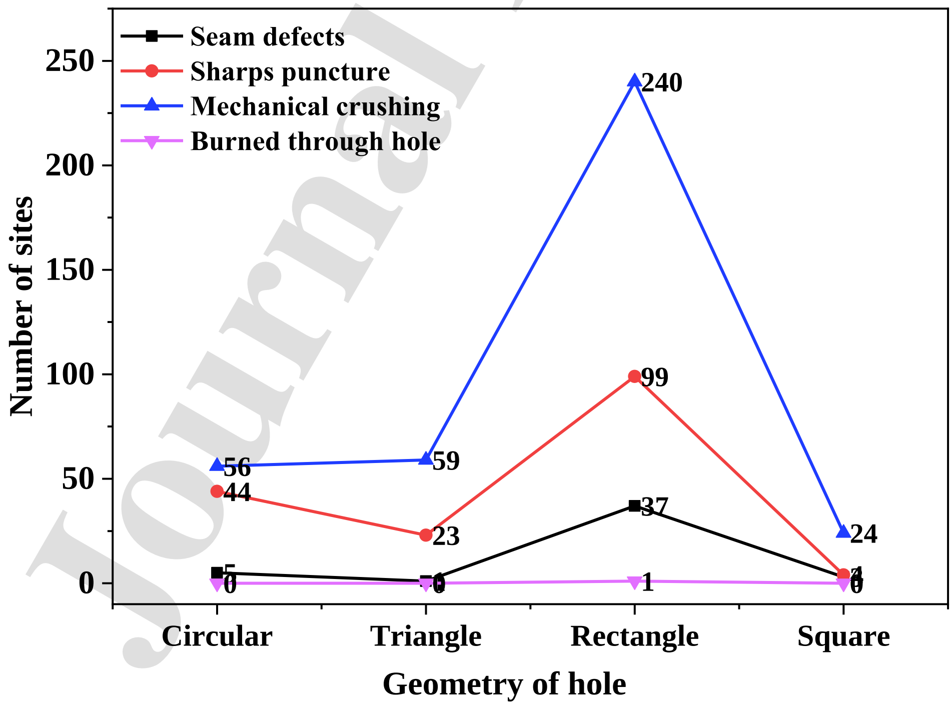


(a)



1000
100
10
1
0.1
Equivalent radius (mm)
0
100
200
300
400
500
600
Sequence number of hole

(b)



Seam defects
Sharps puncture
Mechanical crushing
Burned through hole
250
200
150
100
50
0
Number of sites
240
99
56
59
44
23
37
24
5
1
Circular
Triangle
Rectangle
Square
Geometry of hole

(c)

Figure 3. GMB hole detection results and related parameter statistics: (a) holes per hectare histogram, (b) single logarithmic coordinates of the equivalent radius distribution of 557 holes, (c) number of holes with different geometric shape of seam defects, sharps puncture, mechanical crushing, and burned-through hole.

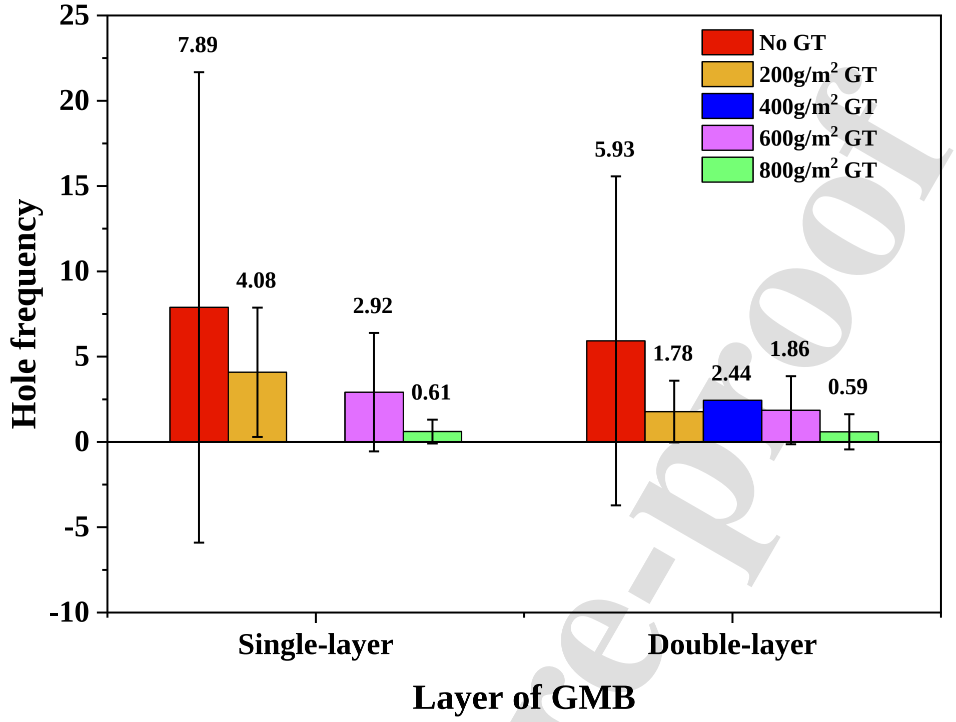
The area of the holes on the HDPE GMB was converted to the equivalent radius of the holes and plotted on a single logarithmic axis with the radius in logarithmic coordinates (Fan et al., 2021b), and Figure 3(b) shows that the equivalent radius is mainly concentrated in the range of 0.3–100 mm.

The shape of the holes is also an essential parameter in the pattern analysis. Since the holes' shape is not strictly “regular” due to the GMB material and many external factors, approximate categorization was chosen for the analysis. Among the 557 holes counted, the main types were rectangular, circular, square, and triangular holes. Figure 3(c) shows the four main types of holes. The statistics show that, among the four main types of holes, the rectangular holes are the most dominant, while the square holes are the least dominant. This result is easily understood, given that rectangular holes are the dominant form of holes caused by seam defects and mechanical crushing. While the square is a particular rectangle, other aspects influence the appearance of square holes. The frequency of circular holes in the form of sharps puncture damage is also relatively high, which may be related to how the HDPE GMB is stressed by the garbage puncture during the damage.

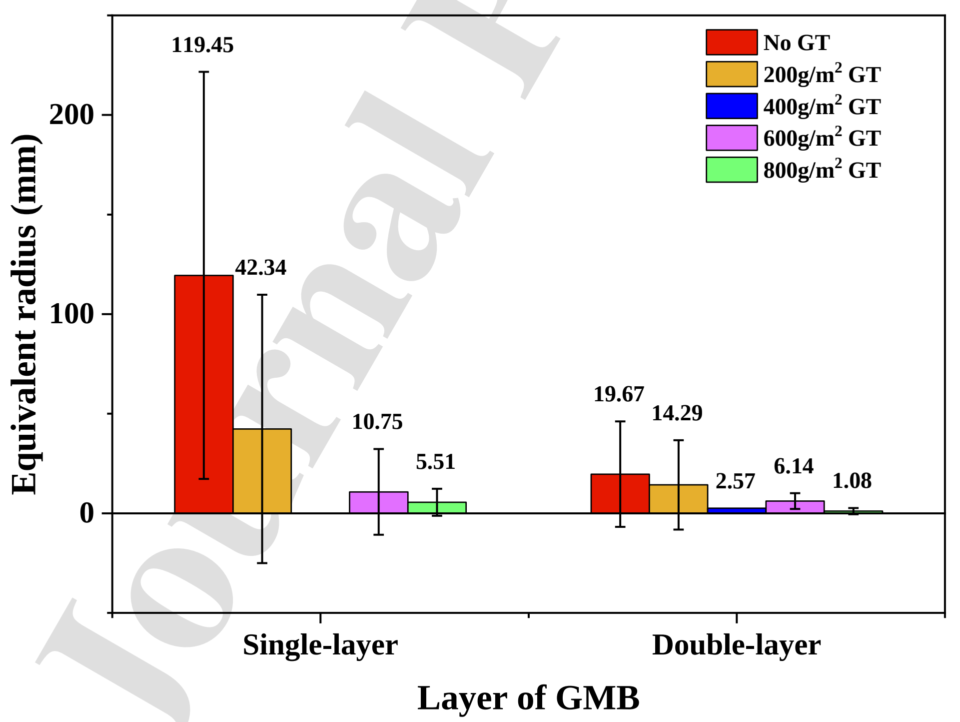
3.2 Correlation factor analysis of geomembrane holes parameters

3.2.1 Analysis of the influence of the number of geomembrane layers on GMB holes

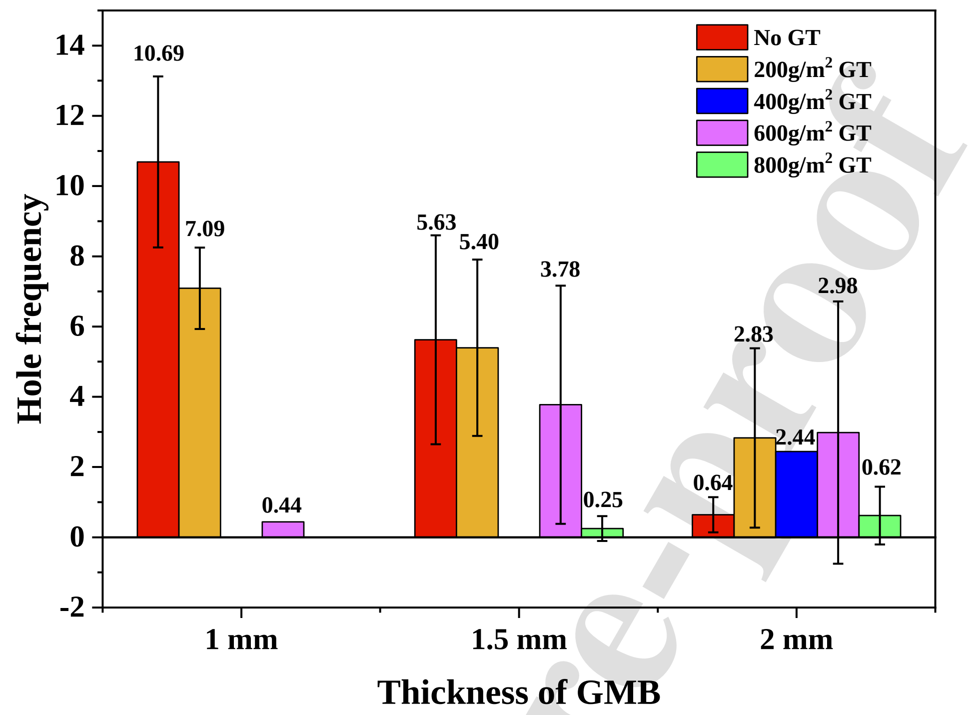
The HDPE GMB plays a crucial role in the composite liner system, as per the technical codes for municipal solid waste sanitary landfill (2013) (GB 50869-2013) and the Standard for pollution control on hazardous waste landfill (2019) (GB 18598-2019). A single layer of HDPE GMB is needed for general domestic waste landfills, whereas hazardous waste landfills require double layers of HDPE GMB. Out of the 55 landfills studied, all had been paved with HDPE GMB, with 23 having a single layer and 32 having a double layer. The double-layer HDPE GMB had a lower hole frequency than the single-layer HDPE GMB. The hole frequency of double-layer HDPE GMB was reduced by 24.8%, 56.4%, 36.3%, and 3.3% with no GT, 200 g/m2 GT, 600 g/m2 GT, and 800 g/m2 GT, respectively, compared to single-layer HDPE GMB. This shows that the composite liner structure of double-layer HDPE GMB can better reduce the number of holes and improve the impermeability of the composite liner system. The error bars of HDPE GMB layers and hole size further support this conclusion. Figure 4(b) shows that the hole sizes on double-layer HDPE GMB are smaller than those of single-layer HDPE GMB, decreasing by 83.5%, 66.2%, 42.9%, and 80.4% with four different densities of GT covering, respectively. This indicates that the structure of double-layer HDPE GMB can better reduce the area of the holes, thereby reducing the leakage volume.


25
20
15
10
5
0
-5
-10
Hole frequency
7.89
4.08
2.92
0.61
5.93
1.78
2.44
1.86
0.59
No GT
200g/m2 GT
400g/m2 GT
600g/m2 GT
800g/m2 GT
Single-layer
Double-layer
Layer of GMB

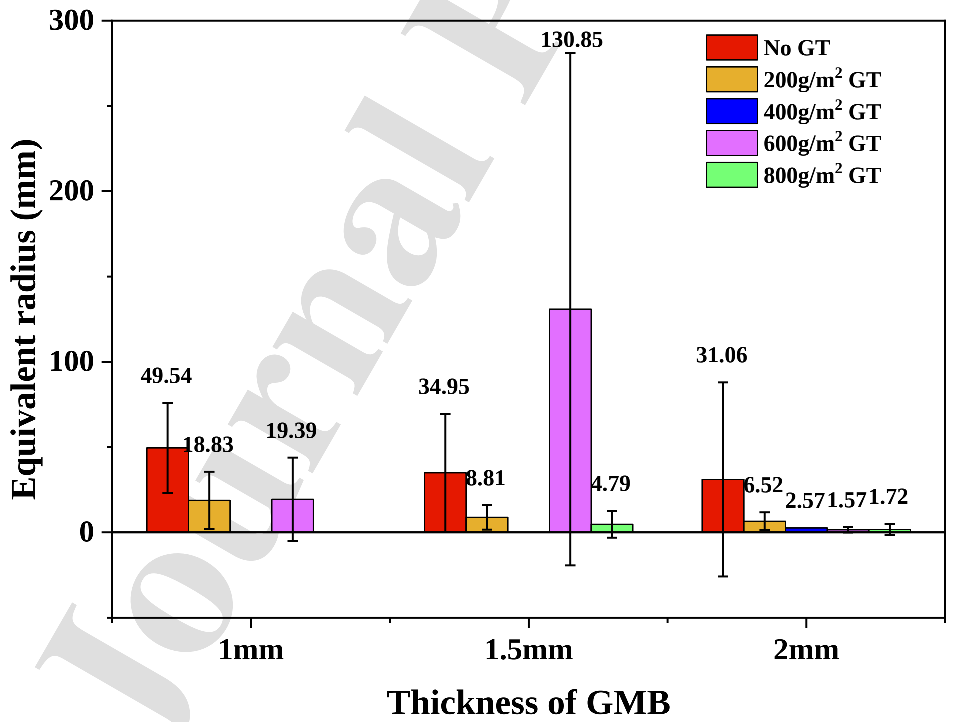
(a)


200
100
0
Equivalent radius (mm)
119.45
42.34
10.75
5.51
19.67
14.29
2.57
6.14
1.08
No GT
200g/m2 GT
400g/m2 GT
600g/m2 GT
800g/m2 GT
Single-layer
Double-layer
Layer of GMB

(b)



(c)



(d)

Figure 4. (a) effect of the number of layers of HDPE GMB on the hole frequency, (b) effect of the number of layers of HDPE GMB on hole size, (c) effect of GMB thickness

on hole frequency, (d) effect of GMB thickness on hole size.

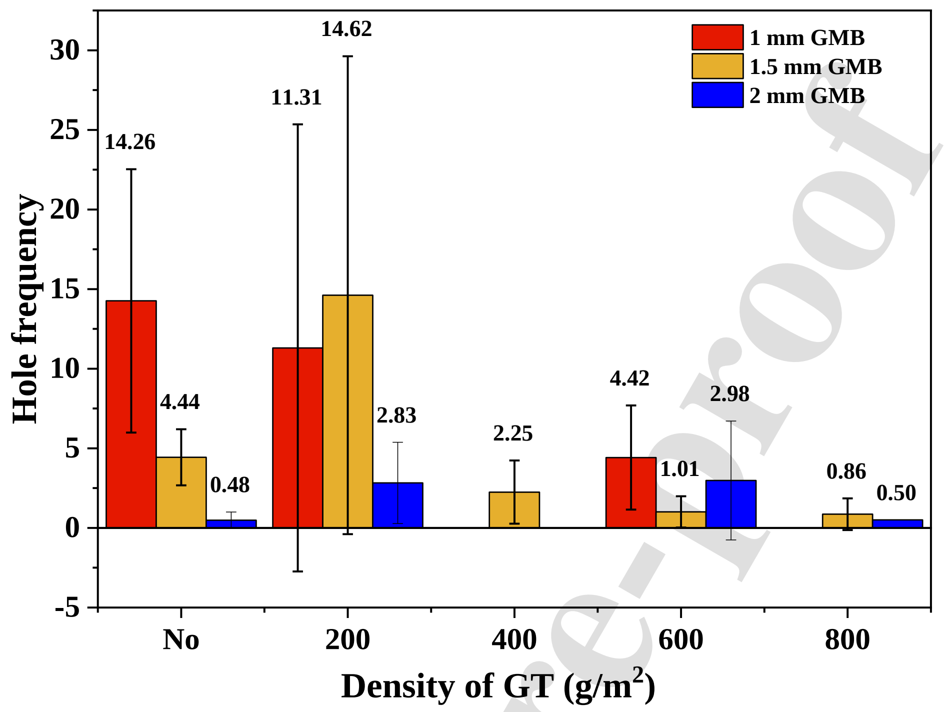
3.2.2 Analysis of the influence of geomembrane layer thickness on GMB holes

According to the Technical Code for Municipal Solid Waste Sanitary Landfill (2013) (GB 50869-2013), the thickness of HDPE GMB for the composite liner system should be at least 1 mm. Out of all the landfills, the HDPE GMB thicknesses mainly vary between 1mm, 1.5 mm, and 2 mm. For landfills with two layers of GMB, only the uppermost layer of HDPE GMB is considered. Out of 9, 16, and 30 landfills, 1-, 1.5-, and 2-mm-thick HDPE GMB, respectively make up that layer. Figure 4(c), which displays the HDPE GMB thickness and hole frequency with error bars, indicates that the hole frequency of HDPE GMB decreases with the thickness of GMB.

The average of the equivalent radius of all holes represents the size of the holes in each landfill. Figure 4(d), which shows the HDPE GMB thickness and the equivalent radius of the landfill with error bars, indicates that the membrane thickness increases as the equivalent radius of the internal breach holes decreases. Compared to the holes on 1 mm GMB covered with 200 g/ m^2 GT, the equivalent radii of holes on 1.5 mm GMB and 2 mm GMB with the same density GT are decreased by 53.2% and 65.4%, respectively. The barrier performance improves as the thickness of the HDPE GMB increases, and the puncture resistance performance improves significantly. Therefore, using a thicker GMB in the design and construction of composite liner systems is more appropriate.

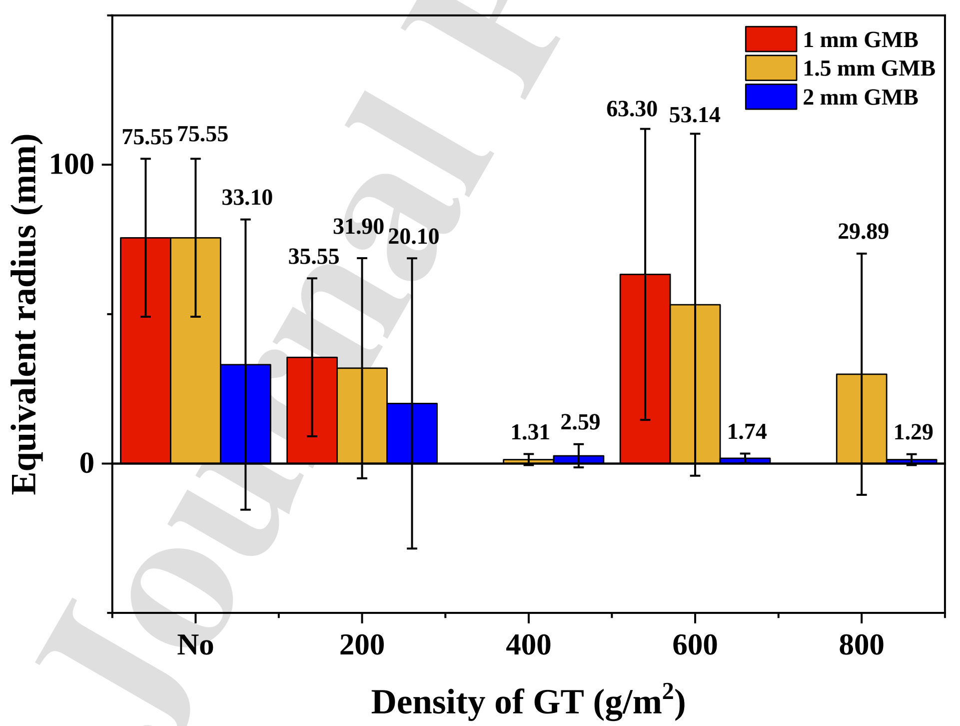
3.2.3 Analysis of the influence of geotextile protective layer density on GMB holes

Geotextiles are frequently used in composite liner systems due to their high tensile strength and ability to adapt to various environments. They are usually placed over the top of the HDPE GMB as a protective layer. In this study, five different densities of geotextiles were tested in various landfills: 200 g/ m^2 (15 sites), 400 g/ m^2 (7 sites), 600 g/m^2 (24 sites), and 800 g/m^2 (19 sites). The Figure 5(b) showed that as the density of the geotextile increased, the frequency of holes significantly decreased, except for some outliers (such as 200 g/m^2 on 1.5mm GMB). Additionally, the equivalent radius of the holes was reduced by 39.2%, 92.17%, 94.7%, and 96.1% compared to no geotextile on 2mm GMB, corresponding to the respective four densities of geotextile used. Geotextiles with a density of less than 400 g/m^2 were found to be ineffective in protecting the HDPE GMB. In comparison, those with a 400 g/m^2 density or above had sound effects on the impermeable liner system, reducing the equivalent radius by about 90%. Therefore, it is recommended that geotextiles with a density of at least 400 g/m^2 be used in composite liner systems, taking into account factors such as landfill construction and economic aspects. Prior to installation, geotextiles should undergo a series of performance tests, such as puncture and tearing resistance tests, to ensure their efficacy in the composite liner system.



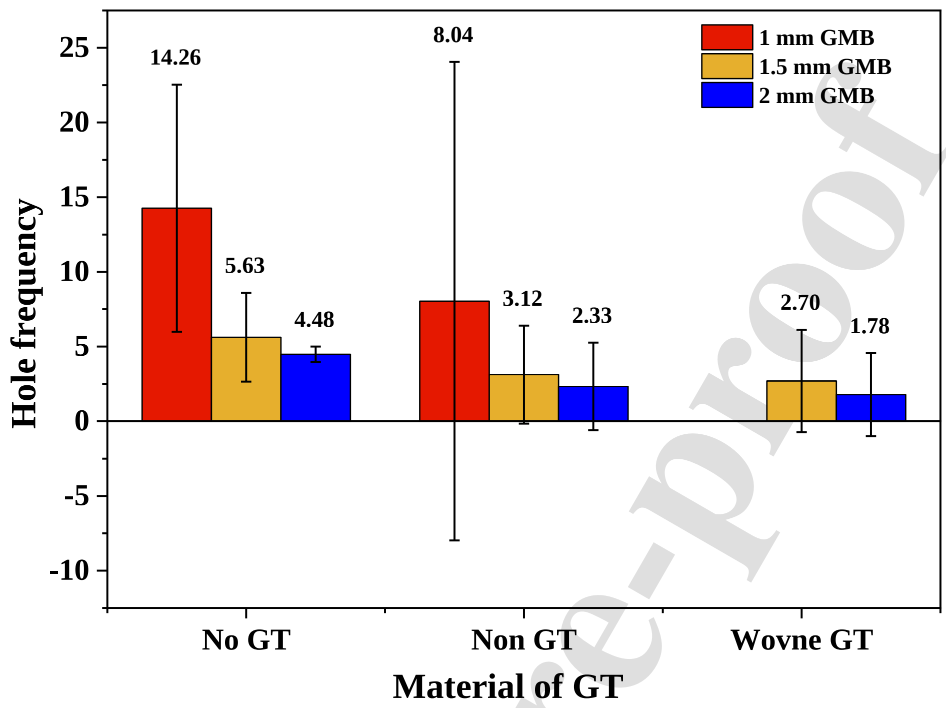
1 mm GMB
1.5 mm GMB
2 mm GMB
Hole frequency
Density of GT (g/m^2)
No
200
400
600
800
14.26
4.44
0.48
11.31
14.62
2.83
2.25
4.42
1.01
2.98
0.86
0.50

(a)

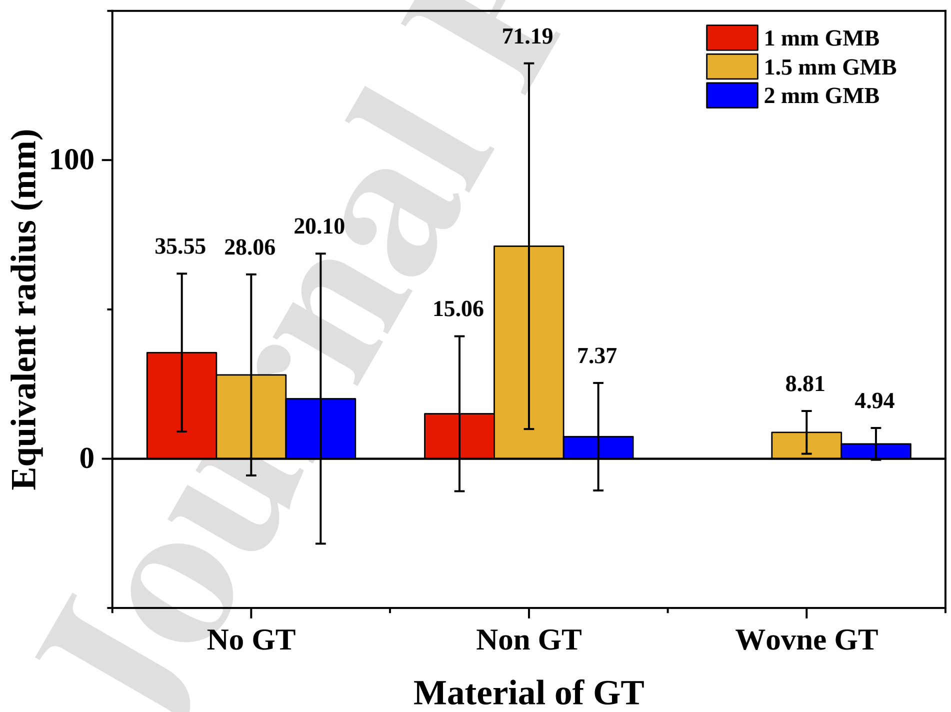


1 mm GMB
1.5 mm GMB
2 mm GMB
Equivalent radius (mm)
Density of GT (g/m^2)
No
200
400
600
800
75.55
75.55
33.10
35.55
31.90
20.10
1.31
2.59
63.30
53.14
1.74
29.89
1.29

(b)



(c)



(d)

Figure 5. (a) effect of geotextile density on hole frequency, (b) effect of geotextile density on hole size, (c) effect of geotextile material on hole frequency, (d) effect of

geotextile material on hole size.

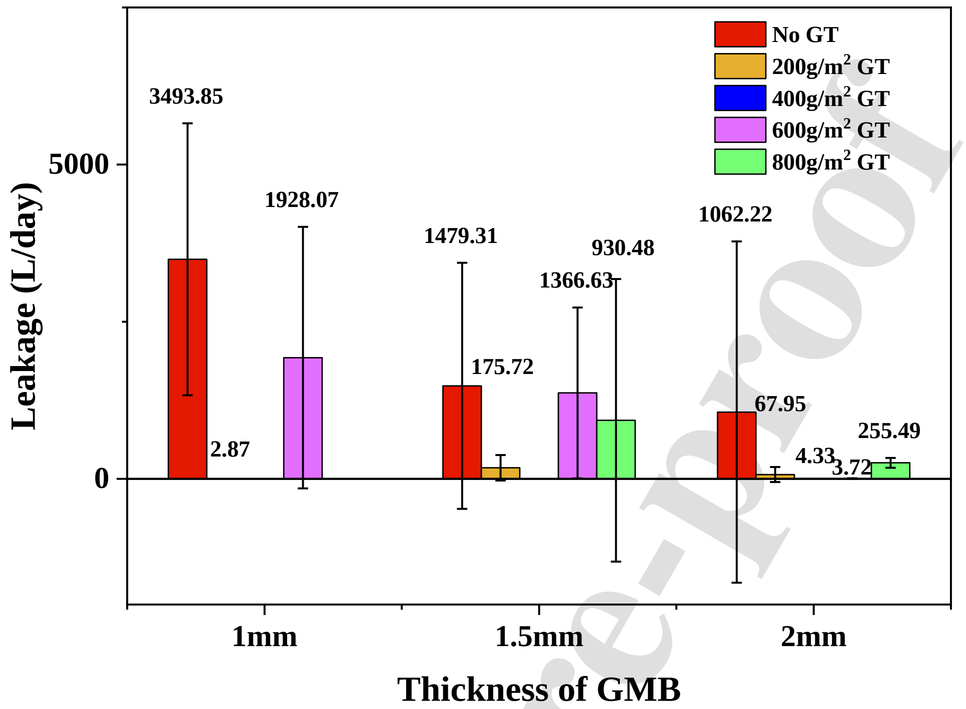
3.2.4 Analysis of the influence of geotextile protection layer materials on GMB holes

Geotextiles used in landfills can be classified as either woven or nonwoven, depending on the material used. Nonwoven geotextiles are further categorized by the type of fiber, such as polyester or polypropylene, and the length of the fiber. Among all counted landfills, there were 13 landfills with woven GT, 27 with nonwoven GT, and 15 without GT. Combining the three types of laying landfills with the hole frequency, Figure 5(c) shows that the hole frequency of landfills without GT is greater than that of landfills with GT. Analysis of hole frequency showed that landfills without geotextiles had greater hole frequency than those with geotextiles. Specifically, the hole frequency of woven geotextiles and nonwoven geotextiles were 52.4% and 44.6% less than that of the holes on 1.5mm GMB, respectively. This demonstrates the crucial role of geotextiles in protecting the HDPE GMB in the composite liner system. The equivalent radius of the HDPE GMB holes was reduced by both woven and nonwoven geotextiles. However, the equivalent radii of HDPE GMB holes under nonwoven GT were higher due to the textile process. Overall, the study emphasizes the importance of geotextiles in the composite liner system for reducing hole size.

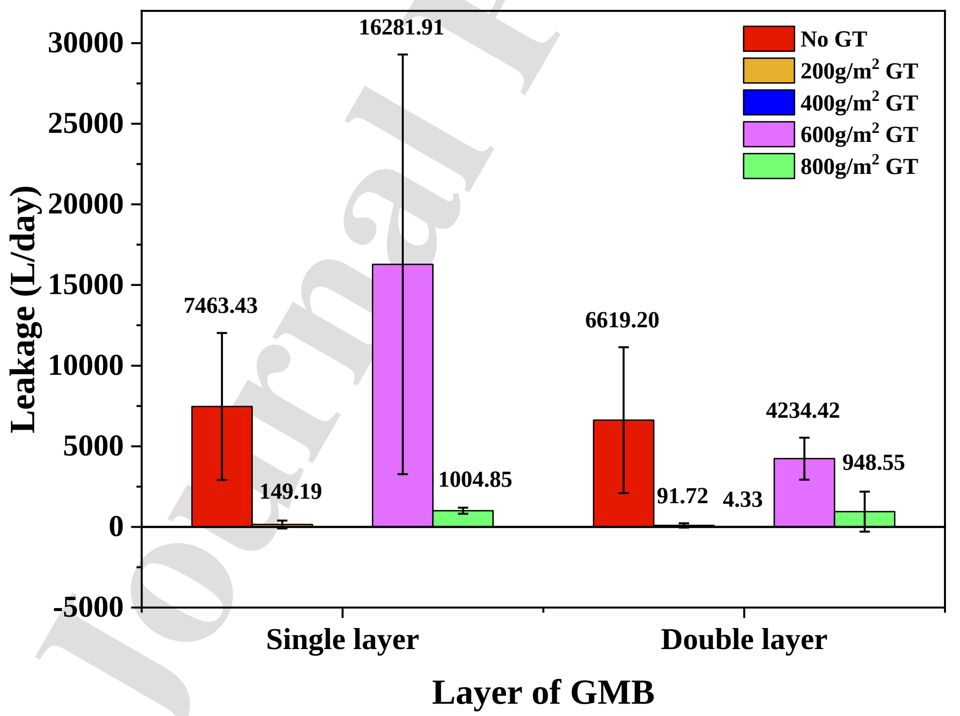
3.3 Leakage analysis of GMB hole

3.3.1 Analysis of related factors of geomembrane leakage

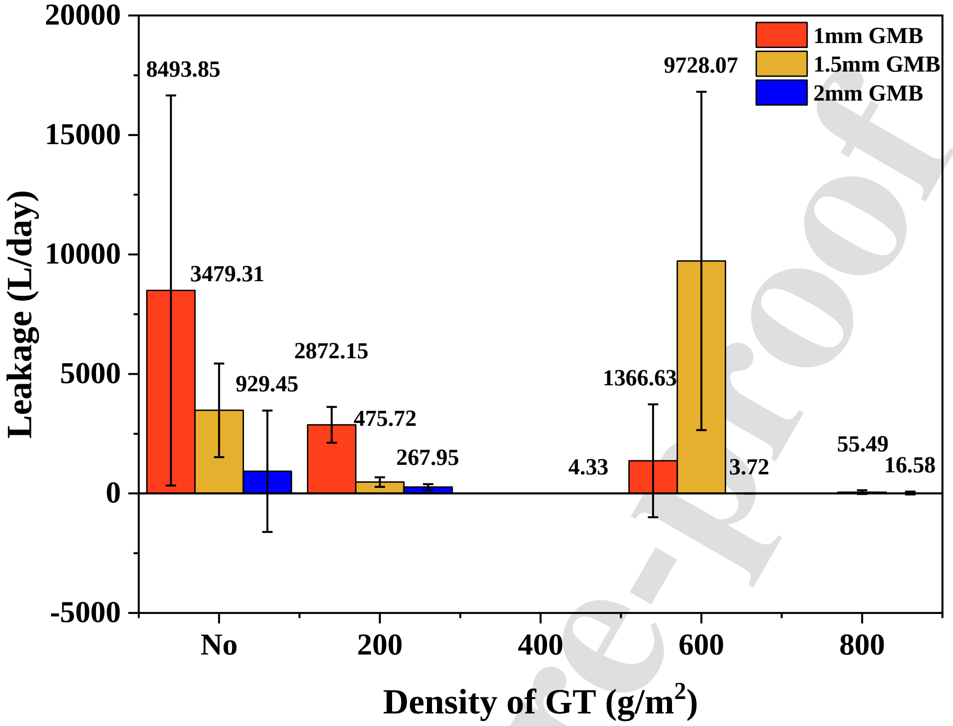
The leakage volume positively correlates with the number of holes per unit area of GMB and the equivalent radius. To investigate the impermeability performance of the composite liner system, the theoretical leakage is supposed to be calculated for the analysis of hole parameters. There is another significant postulated condition that needs to be noticed in this analysis. Holes may appear in both the upper and lower GMB in double layer liner systems. Leakage estimation only be considered on the upper GMB holes, and the reason is that the primary analysis is focused on the influences of upper GMB holes on leakage when estimating by the Rowe-Booker equation. Nevertheless, this would not mean that the holes on the lower GMB are not influential to total leakage.


No GT
200g/m2 GT
400g/m2 GT
600g/m2 GT
800g/m2 GT
3493.85
2.87
1928.07
1479.31
175.72
1366.63
930.48
1062.22
67.95
4.33
3.72
255.49
5000
0
Leakage (L/day)
1mm
1.5mm
2mm
Thickness of GMB

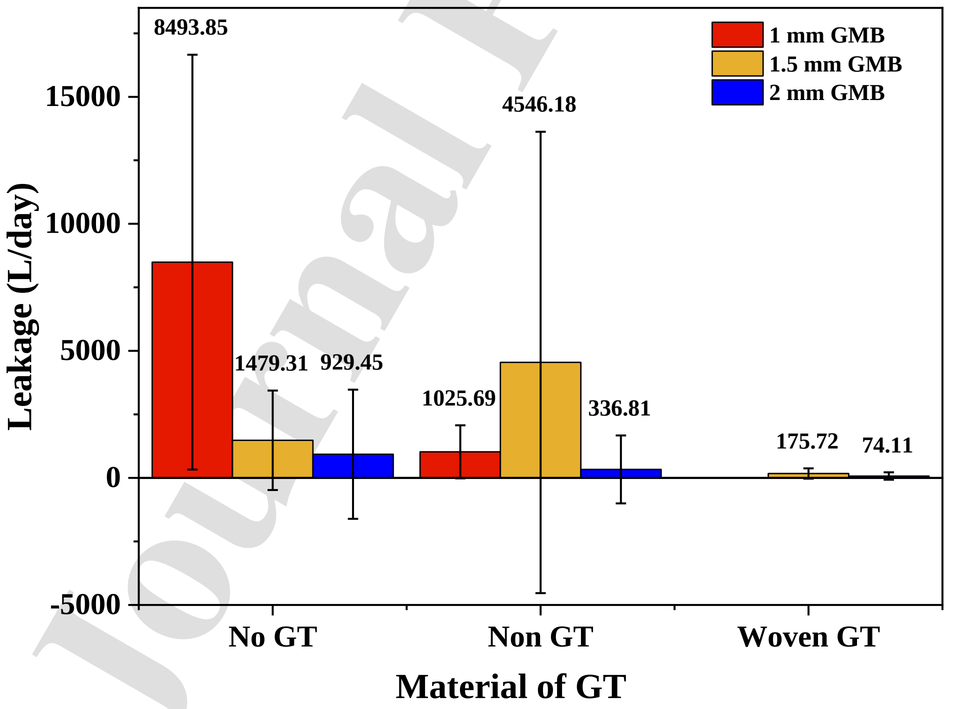
(a)


No GT
200g/m2 GT
400g/m2 GT
600g/m2 GT
800g/m2 GT
16281.91
7463.43
149.19
1004.85
6619.20
91.72
4.33
4234.42
948.55
30000
25000
20000
15000
10000
5000
0
-5000
Leakage (L/day)
Single layer
Double layer
Layer of GMB

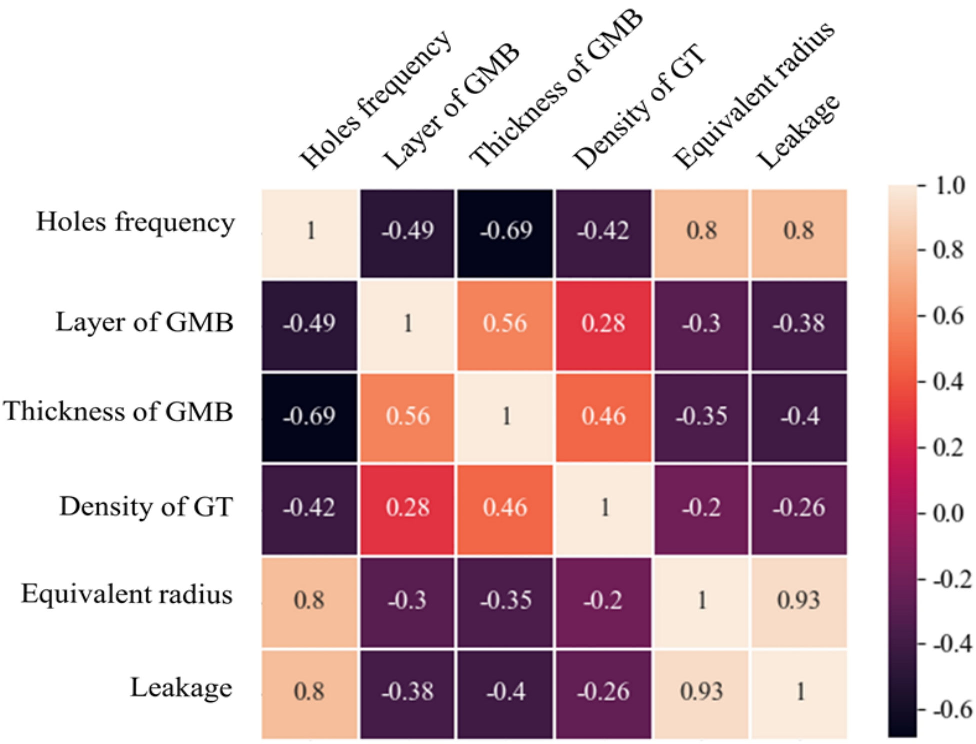
(b)


20000
15000
10000
5000
0
-5000
Leakage (L/day)
8493.85
3479.31
929.45
2872.15
475.72
267.95
4.33
1366.63
9728.07
3.72
55.49
16.58
1mm GMB
1.5mm GMB
2mm GMB
No
200
400
600
800
Density of GT (g/m2)

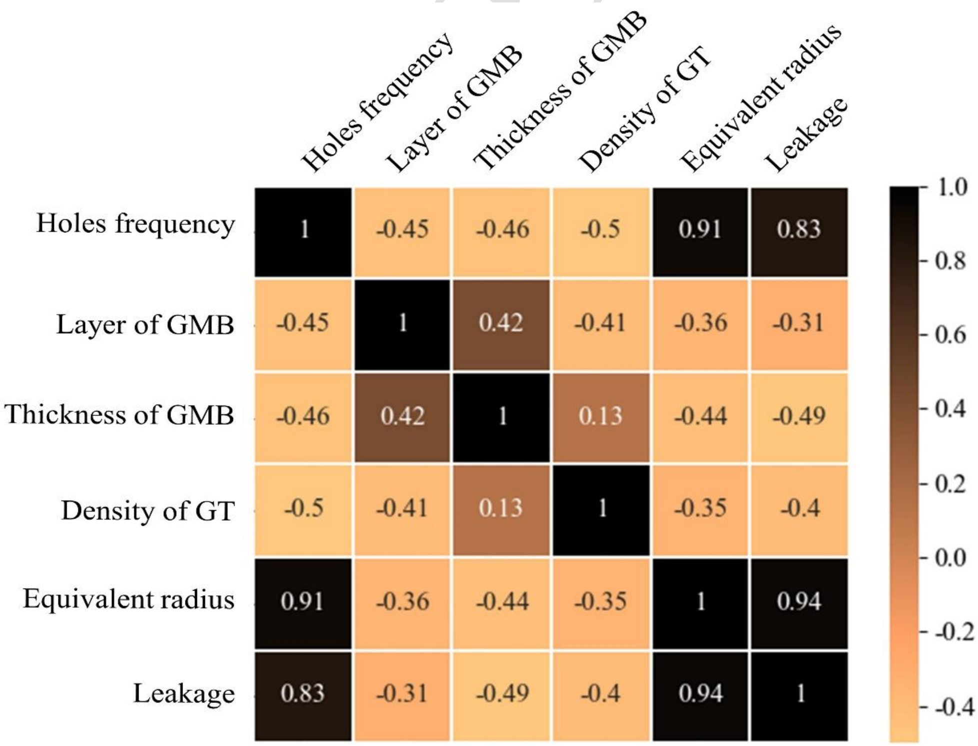
(c)


15000
10000
5000
0
-5000
Leakage (L/day)
8493.85
1479.31
929.45
1025.69
4546.18
336.81
175.72
74.11
1 mm GMB
1.5 mm GMB
2 mm GMB
No GT
Non GT
Woven GT
Material of GT

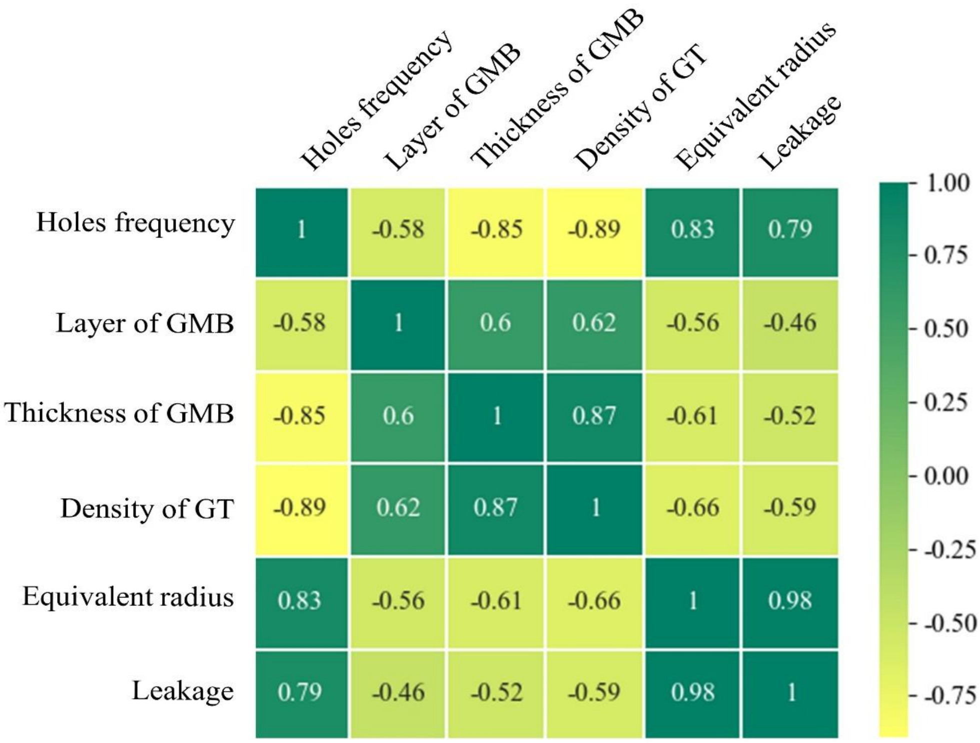
(d)


Holes frequency
Layer of GMB
Thickness of GMB
Density of GT
Equivalent radius
Leakage
Holes frequency 1 -0.49 -0.69 -0.42 0.8 0.8
Layer of GMB -0.49 1 0.56 0.28 -0.3 -0.38
Thickness of GMB -0.69 0.56 1 0.46 -0.35 -0.4
Density of GT -0.42 0.28 0.46 1 -0.2 -0.26
Equivalent radius 0.8 -0.3 -0.35 -0.2 1 0.93
Leakage 0.8 -0.38 -0.4 -0.26 0.93 1
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6

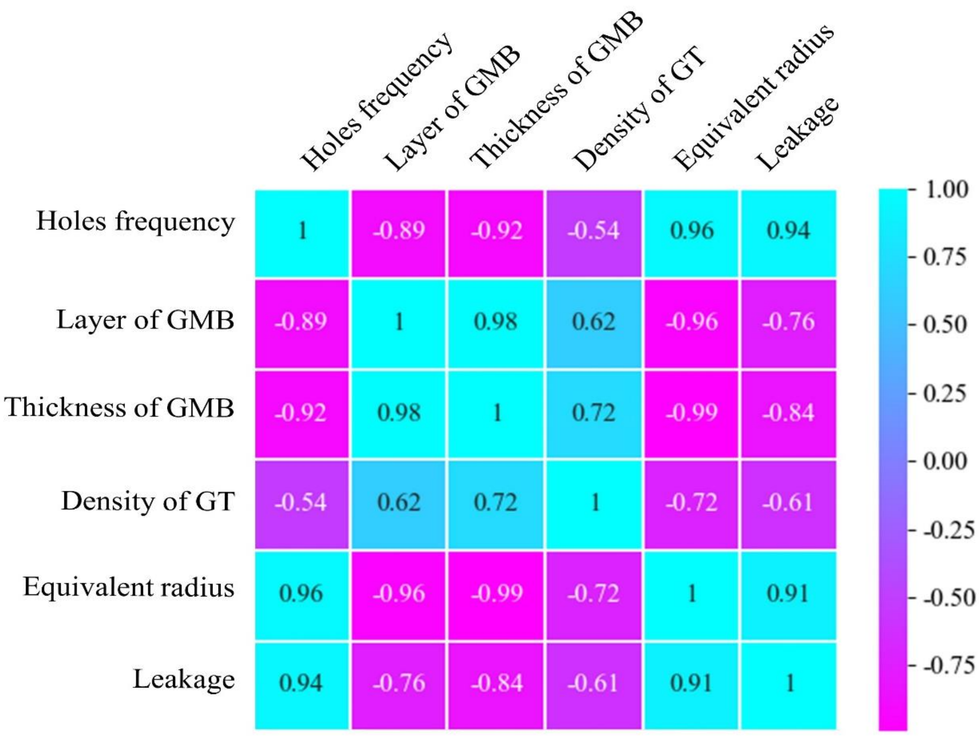
(e)


Holes frequency
Layer of GMB
Thickness of GMB
Density of GT
Equivalent radius
Leakage
Holes frequency 1 -0.45 -0.46 -0.5 0.91 0.83
Layer of GMB -0.45 1 0.42 -0.41 -0.36 -0.31
Thickness of GMB -0.46 0.42 1 0.13 -0.44 -0.49
Density of GT -0.5 -0.41 0.13 1 -0.35 -0.4
Equivalent radius 0.91 -0.36 -0.44 -0.35 1 0.94
Leakage 0.83 -0.31 -0.49 -0.4 0.94 1
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4

(f)


Holes frequency
Layer of GMB
Thickness of GMB
Density of GT
Equivalent radius
Leakage
1 -0.58 -0.85 -0.89 0.83 0.79
-0.58 1 0.6 0.62 -0.56 -0.46
-0.85 0.6 1 0.87 -0.61 -0.52
-0.89 0.62 0.87 1 -0.66 -0.59
0.83 -0.56 -0.61 -0.66 1 0.98
0.79 -0.46 -0.52 -0.59 0.98 1
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75

(g)


Holes frequency
Layer of GMB
Thickness of GMB
Density of GT
Equivalent radius
Leakage
1 -0.89 -0.92 -0.54 0.96 0.94
-0.89 1 0.98 0.62 -0.96 -0.76
-0.92 0.98 1 0.72 -0.99 -0.84
-0.54 0.62 0.72 1 -0.72 -0.61
0.96 -0.96 -0.99 -0.72 1 0.91
0.94 -0.76 -0.84 -0.61 0.91 1
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75

(h)

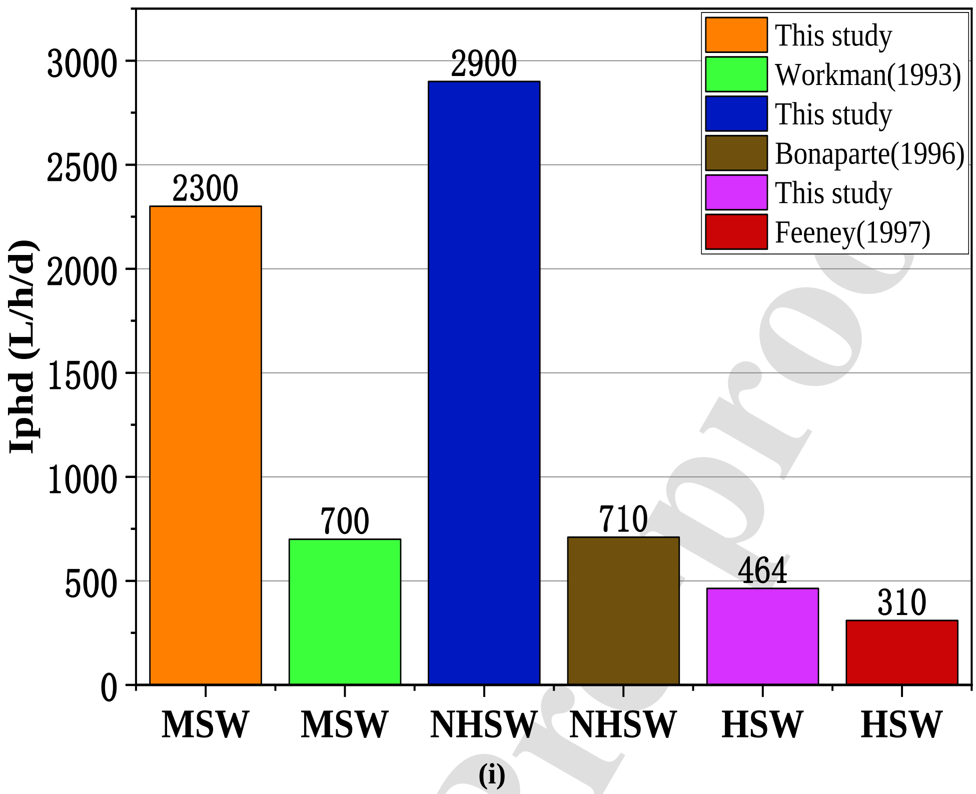


Figure 6. Prediction and evaluation of pore leakage: (a) effect of GMB thickness on leakage volume, (b) effect of GMB layers on leakage volume, (c) effect of geotextile density on leakage volume, (d) Effect of geotextile material on leakage volume, (e) Pearson correlation coefficient for domestic waste landfills, (f) Pearson correlation coefficient for general solid waste landfills, (g) Pearson correlation coefficient for domestic waste incineration fly ash landfills, (h) Pearson correlation coefficient for hazardous waste landfills, (i) Comparison of leakage with other landfills.

One precondition needing to be discussed is that we make a qualitative comparison of leakage with various influencing factors, not a quantitative analysis. Two holes with the same estimating leakage could not represent the same situation on GMB. In all the landfills investigated, it is assumed that the same kind of compacted clay layer has the same hydraulic conductivity. It is presumed that the upper part of the hole has a specific head and the thickness of the permeable layer is specified in the specification. Moreover, the thickness of a waste layer is assumed to be equal in each landfill. The leakage volume of the holes decreases as the thickness of the GMB increases with the same density GT covering, as shown in Figure 6(a). The densities of GT without GT, at 600 g/m^2 and 800 g/m^2, follow a clear pattern, as mentioned before. However, the densities at 200 g/m^2 and 600 g/m^2 do not follow this pattern due to insufficient holes accounted for. Figure 6(b) shows the effect of single- and double-layer GMB on the leakage volume of holes. There are no significant differences in leakage between single- and double-layer GMB except for 200 g/ m^2 GT covering, where the considerable distinction of 200 g/ m^2 GT is due to individual discrete data. This could be explained by the fact that the effects of damage on single- and upper double-layer GMB are similar. The estimated leakages of both single- and upper double-layer GMB with no GT covering reach 7463.43 L/d and 6619.20 L/d, respectively, which obviously exceed leakages of different density GT. The significance of GT protection has been proved again. In the analysis of GT density, it is evident that estimating leakage decreases as the density of GT increases, where the leakage is reduced by one order of magnitude compared with the three kinds of densities (i.e., no GT, 200 g/m^2, 800 g/ m^2). The high leakage on 1.5 mm GMB with 600 g/m^2 GT covering, which has a more significant error bar, is mainly caused by several discrete data whose CQA of landfill is not rigorous. Figure 6(d) plots the leakage amount for woven GT, non-woven GT, and no GT. Excluding the data with a large error bar, the pattern of other data is distinct. Without GT covering, the leakage increased more rapidly than those of nonwoven GT and woven GT. The leakages on 2 mm GMB with three materials GT are estimated as 929.45 L/d, 336.81 L/d, and 74.11 L/d, respectively. Meanwhile, the woven GT has a more pleasing effect on controlling the leakage, which benefits from the better textile effect of the woven GT.

Based on statistical analysis, we have identified that the properties of geotextile, landfill hole frequency, and geomembrane nature have an impact on the final leakage volume. We correlated hole frequency, geomembrane thickness, number of layers, geotextile density, equivalent radius of the hole, and leakage volume, the results are displayed in Figure 6(e)-(h). While the sample sizes of the four landfills vary, we have observed consistent laws. Figure 6(e)-(h) show that hole frequency and pore equivalent radius have a positive correlation with leakage volume. In contrast, the number of layers and thickness of the geomembrane, as well as geotextile density, have a negative correlation with leakage volume. This finding is in line with our previous statistical analysis. Among the four types of landfills, we have found that the thickness of the geomembrane has a higher negative correlation with leakage volume than the number of layers of the geomembrane and geotextile density. Therefore, the thickness of the geomembrane has a more significant effect on the final leakage volume. The highest positive correlation is attributed to the equivalent radius, which is the primary variable in the theoretical equation for leakage. The positive correlation between porosity and leakage is also more excellent, while hole frequency is influenced by both geomembrane thickness and geotextile density. The thickness of the geomembrane has a greater effect on the final leakage volume compared to the geotextile density, which is consistent with the findings of Bacas et al. (2015). After conducting the shear test, Bacas pointed out that the geomembrane plays a more critical role in the composite liner system based on the measured strength law. At the same time, the geotextile parameters are designed and selected based on the use of the geomembrane.

3.3.2 Comparison of leakage with other landfills

In the past century, countries like the United States and Canada have established effective systems to monitor leachate from landfills. These systems regularly analyze the amount of leakage from the composite liner systems of landfills, which helps to study the environmental impact around contaminated sites. China has also begun to pay more attention to landfill leachate leakage and has introduced new requirements for landfill construction quality and process specifications. In this section, the authors compare foreign landfill leachate leakage data to domestic statistics and show the results in a Figure 6(i). The data shows that both municipal and solid waste landfills in China have much higher leakage rates than foreign landfills. The authors reference a study by Othman et al. (1997), who found that foreign landfills with third-party CQA during construction had lower rates of leakage. Some Chinese landfills lack CQA, which often results in poor construction quality of composite liner systems and higher rates of leakage. Othman's statistics show a decreasing trend of leakage with the increase of landfill operation time, and the leakage is also influenced by the rate of waste deposited during operation. This information is valuable for continuing to monitor landfill leakage statistics.

3.4 Applications and perspectives

The safety of landfill leachate leakage has always been a major concern. This study provides valuable data on the field conditions of Chinese landfills after construction, which can serve as a reference for future landfill design and construction. Field statistics show that the complete composite liner system is effective in preventing leachate leakage. However, maintaining the system's integrity and detecting damage in a timely manner is crucial. The study found that the thickness of the geomembrane is the most important factor in preventing seepage. Landfills with a 1mm geomembrane have higher hole frequency and more significant leaks compared to those with thicker geomembranes (1.5mm, 2mm). Therefore, designers must ensure that the thickness of geomembrane meets safety requirements during landfill design. In addition, Rowe equation was applied to fifty-five landfills for leachate leakage estimation after reasonable assumptions in this study. Calculating the amount of leakage allowed for an analysis of how structural differences in the composite liner system affected impermeability, as well as the importance of construction quality in ensuring impermeability. These findings will aid in improving composite liner systems in the future. Additionally, the estimated leakage volume can be compared to the actual flow rate monitored by the landfill, which is crucial for the safe operation and management of the landfill.

The premise of the high-quality barrier function of the composite liner system is to avoid the formation of holes as much as possible and to use more accurate detection technology, while a reasonable prediction of leachate leakage is also essential. Predicted leakage results indicate that a low-quality construction process often leads to high leakage, which emphasizes the need for construction personnel to adhere to process specifications. Further research is required to determine the average leakage rate resulting from a covered geomembrane survey implemented correctly, followed by effective repairs. Estimating leachate leakage is critical for the safety and economic viability of landfills in the long term. In the future, researchers will need to explore more standardized construction quality assurance and advanced leak detection techniques.

4. Conclusions

This research examined 55 different types of landfill composite liner systems in China to detect and analyze GMB holes on site. We evaluated the impact of geotextile and HDPE GMB performances on the occurrence of GMB holes concerning the composite liner system's structural parameters. We found that geomembrane and geotextile performances influence hole parameters and leakage levels, but geomembrane thickness is the main factor. While CQA focuses on the welding process, ensuring the impermeability of the composite liner system is essential. We recommend continued monitoring of landfill leakage and comparison with other landfills to optimize the composite liner system's structural design.

Acknowledgement

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- The basic parameters of holes of 55 landfills in China are statistical.
- The relationship between geometry of holes and structure is analyzed.
- The amount of leakage is estimated and its main influencing factors are analyzed.

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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.