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Preliminary carbon reduction emission assessment with GCLs as vertical barriers for municipal solid waste dump sites in China

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ABSTRACT

As the rise of global carbon emission reduction policies, traditional cement-based, transportation-intensive vertical barriers begin to phase out, and high efficiency and environmental friendly alternatives, such as GCLs, gain increasing popularity. Albeit the apparent advantages, in the era of Carbon-Neutrality target, a quantitative analysis of carbon reduction associated with emerging techniques is not available. This study attempts to make a preliminary effort to access the total carbon emissions in the containment of 27000 waste dumps and 542 sanitary landfills with barriers manufactured under three schemes, including cement (Scheme 1), high-density polyethylene geomembrane and compacted clay liner (Scheme 2), and high-density polyethylene geomembrane and compacted clay liner (GCLs-GM) (Scheme 3). The calculation mothed in 2006 Intergovernmental Panel on Climate Change guidelines is used in this paper. For sanitary landfills, scheme 1 produced 4548.78–11440.13 kt CO_2, scheme 2 produced 155.89–392.04 kt CO_2, and scheme 3 produced 65.08–203.90 kt CO_2. Meanwhile, for waste dumps, scheme 1 produced 226599.52–569895.69 kt CO_2, scheme 2 produced 7765.89–19529.79 kt CO_2, and scheme 3 produced 3241.84–10157.51 kt CO_2. When waste dumps select scheme 3 replacing scheme 1 as vertical barriers, 223357.68–559738.18 kt CO_2 is reduced, which is essentially equivalent to 57.6% of the total annual carbon emissions in Zhejiang province, China. These preliminary results showcased the vast potential of the use of GCLs-GM as barriers for carbon emission reduction in a range of engineering barrier practices involving the containment of vast amounts of solid wastes from mining, industrial, and agricultural operations.

Keywords: carbon emissions, landfill, vertical barrier, GCLs

1 INTRODUCTION

The greenhouse effect is a pressing issue. The China's Climate Change Blue Book (2022) noted continuously increasing global warming and record-breaking values of multi-indices of climate change such as average surface air temperature, coastal sea level, and thickness of the permafrost active layer in China in 2021. In recent years, municipal solid waste (MSW) landfills have received widespread public attention owing to the large amount of greenhouse gases (GHGs) produced from them. In 2010, the United States announced waste landfills to be the third largest anthropogenic source of CH_4 emissions, contributing to 16% of the total CH_4 emissions (EPA, 2012). In the EU region, municipal waste management activities alone realized 18% of the 2012 Kyoto GHG reduction target set for the original 15 EU member states (ISWA, 2009). This situation is similar to that in China, where CH_4 emissions from MSW landfills in provinces increased from 1141.10 Gg in 2003 to 1858.98 Gg in 2013 (Du et al., 2017). Therefore, it is crucial to explore the GHG reduction potential of MSW landfills (Liu et al., 2017).

GHG emissions from landfill systems can be divided into direct and indirect emissions. Direct emissions are directly related to landfill site activities and waste degradation. In contrast, indirect emissions are associated with the landfill but are generated outside the landfill site, such as the provision of diesel fuels, liner materials and electricity consumption (Manfredi et al., 2009). GHG emissions from MSW are the primary source of direct emissions. Zhao et al. (2009) evaluated the current pattern of MSW management with regard to GHG emissions in Tianjin and demonstrated that GHG emissions from the MSW management system amount to 467.34 Mg CO_2 eq. per year, of which 68% are attributed to landfill gas (LFG). Hegde et al. (2003) found that CH_4 and CO_2 emissions from waste at Shan-Chu-Ku landfill site amounted to approximately 171 t and 828 t, respectively, in 1999. Previous studies have shown that the quantity of carbon emissions produced from MSW disposal depends on the disposal modes and that greater amount of CO_2 is produced from sanitary landfills than that from burning (Bian et al., 2022; Wang & Geng, 2015). MSW incineration for energy production and landfill gas utilization at landfill sites are the primary methods for carbon emission reduction (Li et al., 2011; Yang et al., 2013).

Liner materials are one of the sources of indirect emissions from landfills. The vertical barrier is a crucial part of the lining system at landfills, preventing contamination of groundwater and soil by landfill leachate. Cement slurry lined with soil particles forming a low-permeability barrier intercepts the migration path of contaminant solute. In the past decades, cement vertical barrier is often used as the preferred alternative in landfills (Xi et al., 2013). With the advancement in related materials science, most global technical codes have specified the use of composite liners, including high-density polyethylene (HDPE) geomembrane (GM), compacted clay liner (CCL), and geosynthetic clay liner (GCL), as vertical barriers (Xie et al., 2011). Unfortunately, more than 27000 waste dumps in China were built before 2010 using non-standard liner systems (Wan et al., 2022). Such waste dumps are prone to leachate leakage, which results in serious contamination of the surrounding environment. Meanwhile, there are 542 sanitary landfills in China in 2021. Deteriorating vertical barriers with service time lead to potential leachate leakage. Therefore, vertical barriers need to be added to these landfills to prevent further pollution. When added in great numbers, these barriers produce high CO_2 emissions. However, little attention has been paid to the carbon emissions of the vertical barriers.

Therefore, this study (1) calculates carbon emissions of three common vertical-barrier schemes in a landfill, including cement (Scheme 1), HDPE GM and CCL (Scheme 2), and HDPE GM and GCL (Scheme 3), and (2) roughly analyzes the areal demand for the vertical barriers and determines their carbon emissions in all waste dumps and sanitary landfills in China.

2 METHODOLOGY

2.1 Calculation method

Carbon emissions of the three vertical-barrier schemes were calculated using the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines ("Eggleston, "Buendia, "Miwa, "Ngara, & "Tanabe, 2006). The most commonly used method is combining “activity data” (AD) with “emission factors” (EFs). “Activity data” represent the information about the occurrence degree of anthropogenic activities, and “emission factor” is the coefficient that characterizes carbon emissions per unit activity. For example, the consumption of cement constitutes activity data, and the carbon emission per unit cement is an emission factor. Therefore, the fundamental equation calculating carbon emissions is expressed as follows:

$$\text{emission} = AD \times EF \tag{1}$$

In general, activity data and emission factors are obtained from national statistical services, IPCC emission factor databases, international organizations, journals, and other documents.

2.2 Activity data analysis

The compartment areas of 60 nationwide landfills were quantified based on public information from the State Statistical Bureau of the People's Republic of China. The result shows a normal distribution, as presented in Figure 1, with a mean value of 17.6 and standard deviation of 9.6. A confidence interval of 80%, with upper and lower limits of 29.9 and 5.3, respectively, was calculated. This indicates that the area of 80% landfills is in the range of 5.3–29.9 hm^2. Assuming that the area of the landfill is a standard circle, its radius ranges from 259.8 m to 617.0 m, with an average radius of 473.4 m. Thus, three landfill models, designed according to the Technical Code for Municipal Solid Waste Sanitary Landfill (GB 50869-2013), represented small (model 1), mean (model 2), and large (model 3) size of the landfill (Figure 2). The slope gradients of the landfill and cover are 1:2 and 1:10, respectively, and the slope height of landfill is 12 m.

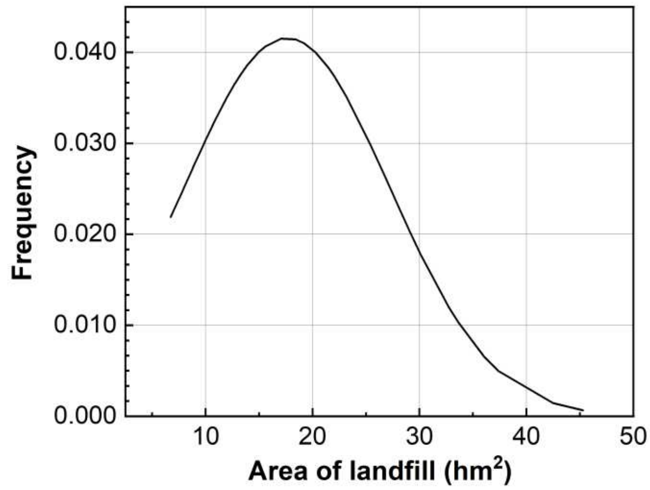
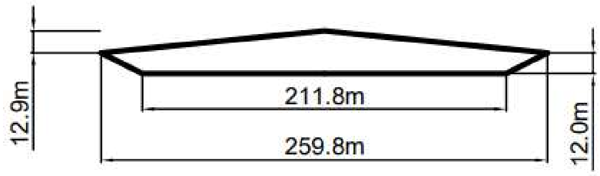
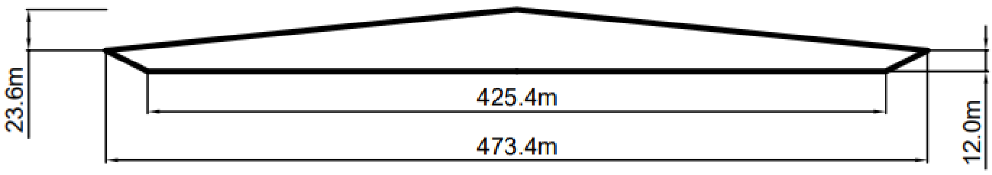


Figure 1. *Normal distribution of compartment areas of 60 landfills in China*



(a)



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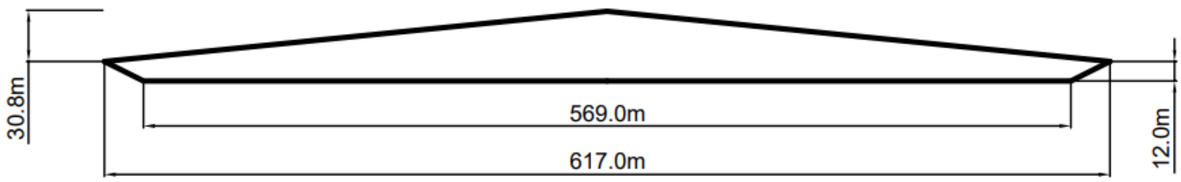


(c)

Figure 2. *Three designed models of landfill: (a) Small size landfill. (b) Mean size landfill. (c) Large size landfill.*

Activity data of three vertical-barrier schemes, including cement, HDPE GM and CCL, and HDPE GM and GCL, were analyzed in this study (Table 1). The thickness and density of cement were 60 cm and 1.3 g/cm^3 and those of HDPE GM were 2 mm and 1.3 g/cm^3, respectively. Moreover, the areal density of GCL was 6000 g/m^2, and the thickness of CCL was 50 cm. The material parameters were in accordance with the Technical Code for Municipal Solid Waste Sanitary Landfill (GB 50869-2013). The activity data of materials were calculated as follows:

$$AD = S \times AM \quad (2)$$

where S and AM represent the area and amount of material per unit area of the vertical barrier, respectively.
The areal demand for vertical barriers for each model was calculated as follows:

$$S = l \times \pi \times (R_1 + R_2) \quad (3)$$

where l is the length of slope and R_1 and R_2 are the subsurface and surface radii of the landfill, respectively. From Eq. (2), the areal demand of the vertical barrier of model 1 (M1), model 2 (M2), and model 3 (M3) were calculated to be 19876.96 m^2, 37883.19 m^2, and 49990.48 m^2, respectively.

Table 1. *Activity data of cement, high-density polyethylene (HDPE), GCL, and compacted clay liner (CCL)*

Activity	Material			Transportation[a]		
	M1	M2	M3	M1	M2	M3
Cement	15504.03 t	29548.89 t	38992.57 t	23280 km	44340 km	58500 km
HDPE	37.77 t	71.98 t	94.98 t	60 km	120 km	150 km
GCL	19876.96 m^2	37883.19 m^2	49990.48 m^2	180 km	360 km	450 km
CCL	19876.96 m^2	37883.19 m^2	49990.48 m^2	23880 km	45480 km	60000 km

[a] Carbon emissions during transportation are calculated by assuming that the raw materials are transported for 30 km by a gasoline vehicle, whose bearing capacity is 20 t per unit time (Dai et al., 2011).

2.3 Emission factor collection

In this study, only the CO_2 emitted by the raw materials and that emitted during their transport from the place of trade to the landfill was considered. The CO_2 emissions produced during construction, such as earth excavation, lighting, and other processes were not considered. The emission factors of cement, HDPE GM, CCL, GCL, and transportation are shown in Table 2.

Table 2. *Emission factors of cement, high-density polyethylene (HDPE), GCL, and compacted clay liner (CCL)*

Activity		Emission factor	Reference
Material	**Cement**	0.54 t CO_2-eq. t^{-1} cement	(Zhang et al., 2021)
	HDPE	1.85 t CO_2-eq. t^{-1} HDPE	(EASEWASTE database)
	GCL	4 kg CO_2-eq. m^{-2} GCL	(EAGM, 2022)
	Compacted Clay	9.9 kg CO_2-eq. m^{-2} 50 cm thick compacted clay	(EAGM, 2022)
Transportation		876.2 g CO_2-eq. km^{-1}	(Cai & Xie, 2010)

3 RESULTS AND DISCUSSION

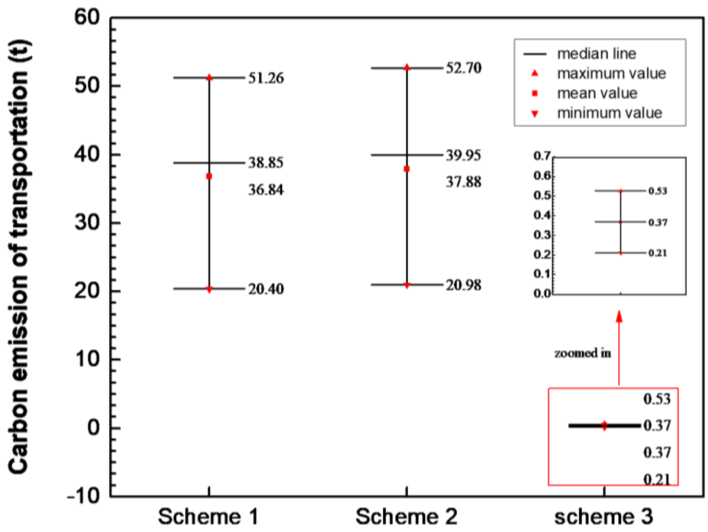
3.1 Carbon emissions of three vertical barrier schemes for one landfill

As shown in Table 3, the maximum carbon emissions were produced using scheme 1 as a vertical barrier in a landfill, which ranged from 8392.57 t to 21107.25 t. In contrast, scheme 3 produced the minimum CO_2 emissions, ranging from 149.59 t to 376.20 t. Additionally, compared to scheme 3, scheme 1 and 2 produced 56 and 2 times more CO_2 emissions, respectively. From activity data and emission factor analyses, it is clear that despite the emission factor of HDPE being higher than that of cement, the activity data of cement were much larger (410 times) than those of HDPE. This is because, under the condition of meeting impermeability requirement, the amount of cement used for vertical barriers is relatively higher than that of HDPE. Meanwhile, the activity data of cement, GCL, and CCL were of the same order of magnitude, but the emission factor of cement was relatively higher than that of the other two materials. Thus, scheme 1 produced the maximum CO_2 emissions.

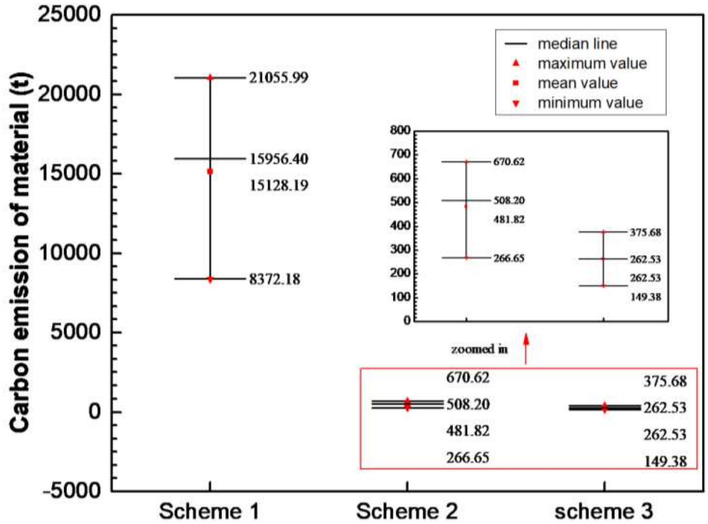
Table 3. *Carbon emissions of three vertical barrier schemes for one landfill*

Carbon emissions (t)	M1	M2	M3
Scheme 1	8392.57	15995.25	21107.25
Scheme 2	287.63	548.16	723.33
Scheme 3	149.59	285.11	376.20

Carbon emissions from material and transportation of three schemes were calculated, and the results are shown in Figure 3. Scheme 1 and 2 produced approximately the same amount of CO_2 from the transportation, ranging from 20 t to 55 t. In contrast, scheme 3 produced only little CO_2, less than 1 t, which could be attributed to the thin HDPE and GCL materials used in scheme 3 that require less volume of transportation. For the raw materials, scheme 1 produced comparatively more CO_2 emissions than the other two schemes, with carbon emissions ranging from 8372.18 t to 21055.99 t. Carbon emissions produced from the material were three order of magnitudes higher than those from transportation, indicating that carbon emissions are primarily produced from the material and that the total proportion of CO_2 from transportation is less than 1%.



(a)



(b)

Figure 3. *Carbon emissions from transportation (a) and materials (b) of three vertical barrier schemes for one landfill*

3.2 Vertical barrier areal requirement and carbon emission distribution

3.2.1 Sanitary landfill

According to the areal demand of vertical barriers of a landfill calculated in section 2.2, the total barrier demand for 542 sanitary landfills was estimated to be 10.77–27.09 km^2. Moreover, nationwide carbon emissions of three vertical barrier schemes were calculated. The results showed that scheme 1, 2, and 3 produced 4548.78–11440.13 kt, 155.89–392.04 kt, and 65.08–203.90 kt CO_2, respectively. The nationwide carbon emission distribution using scheme 3, calculated based on model 2, was selected for analysis, and the results are shown in Figure 4. The carbon emission distribution of the other two schemes calculated based on different models are not shown in the paper.

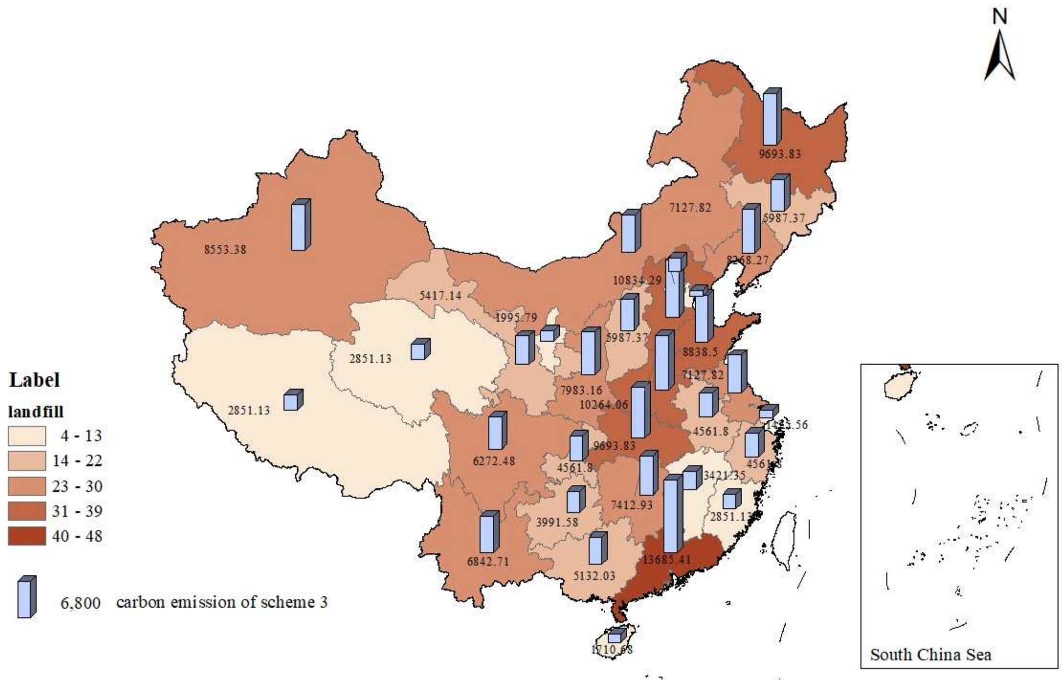


Figure 4. *Nationwide distribution of carbon emissions using scheme 3 as a vertical barrier in sanitary landfills*

As evident from results, carbon emissions in Heilongjiang, Henan, Hebei, Shandong, Hubei, and Guangdong are higher than those in other provinces, among which Henan, Hebei, and Guangdong produce more than 10,000 tons of CO_2, whereas those of Tianjin, Shanghai, Hainan, and Ningxia account for less than 2000 t. Except Heilongjiang, most of the provinces with high carbon emissions have a relatively large population base. The population of Henan, Hebei, Shandong, and Guangdong exceeds 70 million. This indicates that population has a substantial impact on carbon emissions of vertical barriers. Generally, population and MSW exhibit positive correlations, and the increasing amount of MSW boosts demand for landfills. Therefore, differences in carbon emissions of provinces were also deemed reasonable.

3.2.2 Waste dump

More than 27000 nationwide waste dumps are prone to a risk of leachate leakage. Therefore, vertical barriers need to be urgently employed to prevent further diffusion of contaminants at waste dumps. The total areal demand for vertical barriers for waste dumps was estimated to be 536.68–1349.74 km^2. Carbon emissions of three vertical barrier schemes are shown in Figure 5. The results showed that scheme 1, 2, and 3 produced 226599.52–569895.69 kt, 7765.89–19529.79 kt, and 3241.84–10157.51 kt CO_2 at waste dumps, respectively. Zhejiang province produced 387975 kt CO_2 in 2021 (Meng Li, 2017; Zheng et al., 2018). The carbon emissions under scheme 1 used in 27000 waste dumps nationwide are essentially equivalent to 58.4% of one-year carbon emissions generated in Zhejiang. These findings indicate that new added barriers have a great potential for reducing carbon emissions.

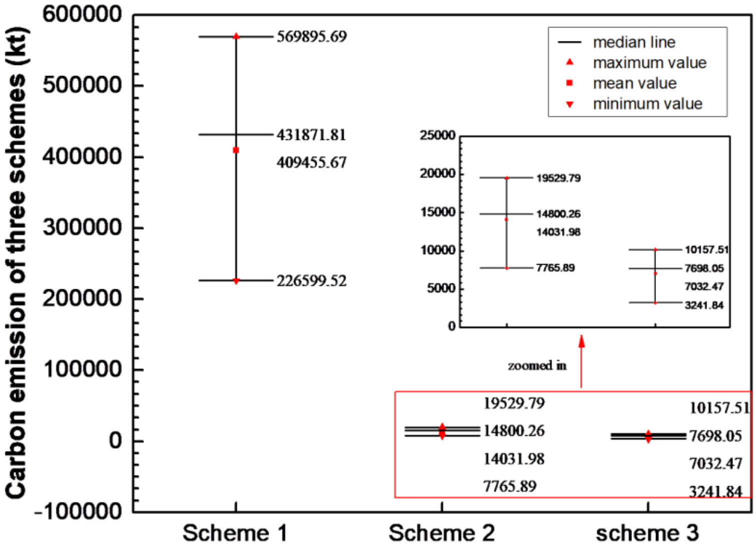


Figure 5. *Carbon emissions of three schemes used as vertical barriers in 27000 waste dumps*

3.3 Economic analysis

Taking a mean size landfill model as an example. Table 4 compares the costs of three schemes, based on the required amounts of materials listed in Table 1 and the unit prices set according to current market prices. As shown in Table 4, cement has the highest cost, while HPDE+GCL has the lowest cost. Although the unit prices of materials are influenced by various factors such as region, market supply and demand, raw material prices and government policies, and fluctuates within a small range, the cost of HDPE+GCL is lower one to two order of magnitudes than that of the other two schemes indicating HDPE+GCL is economical as vertical barrier materials. Moreover, HDPE+GCL requires less transport (as indicated in Table 1) and consequently has lower associated transportation costs.

Table 4. *Comparison of material costs for the three schemes.*

Scheme	Cement	HDPE+CCL		HDPE+GCL	
		HDPE	CCL	HDPE	GCL
Amount	29548.89 t	71.98 t	37883.19 m^2	71.98 t	37883.19 m^2
Unit price	450 RMB/t	9000 RMB/t	70 RMB/m^2	9000 RMB/t	8 RMB/m^2
Gross price （RMB）	13297000.5	3299643.3		950885.5	

4 CONCLUSION

This study analyzed GHG emissions of three vertical barrier schemes based on three landfill models. The areal demand for the vertical barrier in nationwide landfills was also calculated. Moreover, the total GHG emissions of the newly added and updated barriers in China were determined.

(1) The results demonstrate that CO_2 emissions from scheme 1, 2, and 3 in a landfill were 8392.57–21107.25 t, 287.63–723.33 t, and 149.59–376.20 t, respectively. A comparative analysis of carbon emissions of three barrier schemes reveals that when scheme 3 is used as a vertical barrier, least CO_2 emissions are produced. This indicates that HDPE GM and GCL are more environmentally friendly liner materials than the two others. Moreover, our findings show that the carbon emissions of vertical barriers are primarily generated from the material, and the total proportion of CO_2 from transportation is less than 1%.

(2) The new added barriers for sanitary landfills and waste dumps exhibit a great potential for carbon emission reduction. The areal demands for vertical barriers for sanitary landfills and waste dumps were

estimated to be 10.77–27.09 km^2 and 536.68–1349.74 km^2, respectively. It is known that millions of tons of carbon dioxide are emitted from barriers. We found that for sanitary landfills, scheme 1 produced 4548.78–11440.13 kt CO_2, scheme 2 produced 155.89–392.04 kt CO_2, and scheme 3 produced 65.08–203.90 kt CO_2. For waste dumps, scheme 1 produced 226599.52–569895.69 kt CO_2, scheme 2 produced 7765.89–19529.79 kt CO_2, and scheme 3 produced 3241.84–10157.51 kt CO_2. When waste dumps select scheme 3 replacing scheme 1 as vertical barriers, 223357.68–559738.18 kt CO_2 is reduced, which is essentially equivalent to 57.6% of one-year carbon emissions in Zhejiang. The majority of the provinces with high carbon emissions from vertical barriers have a sizable population, indicating that population has a relative positive impact on carbon emissions of vertical barriers.

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