Pollution mitigation and carbon emission reduction through landfill restructuring: A case study in Nanjing City, China

Jing Ma[1, 2], Zhanbin Luo[2], Fu Chen[1,2,3*], Qianlin Zhu[1], Gangjun Liu[3], Yongjun Yang[2]

[1] Low Carbon Energy Institute, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China

[2] Schoolof Environment Science and Spatial Informatics, China University of Mining and Technology, Xuzhou, Jiangsu 221008, China

[3] Geospatial Sciences, College of Science, Engineering and Health, Royal Melbource Instituteof Technology University, Melbourne, Victoria, 3000, Australia

* Corresponding author: Email: chenfu@cumt.edu.cn; tel.:+86051683883501; fax:+86051683883501

Abstract:

China's new environmental standards have forced many landfills in China to be upgraded or rebuilt. A technical process has been established in this study, which is feasible for city solid waste landfill upgrading in China. The feasibility of landfill reconstruction, pollution reduction, and benefit of CO_2 mitigation have been assessed according to field surveys of five formal landfills and four informal landfills in Nanjing city. The results show that only four landfill sites in Nanjing city are suitable for upgrading. The daily processing capacities of the existing landfills have been unable to meet the growing city solid wastes, making reconstruction of the landfills imperative. The reconstructed Jiaozishan landfill has effectively mitigated the pollution of leachate by using the "bottom rain sewage diversion" and zoning planning technology. Although the landfill scale has expanded by 60.7% in 2015, the actual output of leachate has been reduced by 5.84% compared to 2011. After reconstruction, the CO_2 emission reduction was about 55,000-86,000 tons per year, in which the biogas power generation replaced the fossil fuels, accounting for the largest proportion of up to 45000-60000 tons per year. The photovoltaic power generation on the overlying land has not only reduced the CO_2 emissions to 26,000-30,000 tons per year, but also has brought in continuing income from electricity selling. The technical process is essential for the developing countries such as China, which has lacked long-term financial support for garbage landfill operation management.

Keywords: Municipal solid waste; landfill restructuring; leachate control; pollution mitigation; CO_2 emission reduction

1. Introduction

Although cities all over the word are trying hard to reduce the emission of solid waste [1], it is frustrating that global waste will undoubtedly exceed 2.2 billion tons by 2025 [2]. The urbanization level of China has increased rapidly within the past 30 years, at around 700 million people, and the country already has the most urban residents in the world [3]. However, the system of municipal solid waste collection, disposal, and recycling could not keep up with the rapid pace of urban development. Many municipal solid wastes have been stacked in the surrounding areas of the city, and the phenomenon of "garbage siege" is common in developing countries such as China [4-6]. This phenomenon stems from three main reasons: first, the awareness of environmental protection of urban residents is weak. People in the city habitually throw solid wastes in the urban fringe areas and these wastes gradually accumulate, resulting in "garbage siege" [7]. Second, the managers have insufficient experience in urban governance, and they cannot foresee the rapid growth of the urban population. Moreover, the municipal disposal capacity is not enough to cope with the growing urban solid waste production [8]. Third, some small and medium-sized cities of developing countries lack sufficient financial resources. Those limited financial resources must be preferentially used for the construction of the city's most basic infrastructure and public facilities, such as traffic, electricity, water supply, and so on [9]. Previous researches have indicated that that if the urban solid waste is handled improperly, not only will the cityscape be affected, leading to the decline of urban tourism and land value, but the urban environment would also be affected, which would cause groundwater and soil pollution, and even threaten food safety [10-16]. Composting, biodegradation, incineration, open-air piling, sanitary landfill, and others are currently the primary disposal methods of municipal solid waste. However, low efficiency of fertilizer and a high cost of biological treatment are some disadvantages of the composting method. Meanwhile, both could just deal with organic degradable wastes [17]. The cost of the incineration method is high, the incombustible part and ash need to be disposed, and it easily produces secondary pollution. Most developed countries are using the sanitary landfill method, which could simultaneously landfill organic and inorganic waste, and the cost is just 1/ 8-1/ 15 of the incineration method [18]. The engaged landfill sites in China are currently more than 2,000, but the configuration facilities of most landfill sites are missing and the pollution control effect is poor. This phenomenon was common in landfill sites of China [19]. Since July 1, 2011, the People's Republic of China has implemented a new "Standard for Pollution Control of Domestic Refuse Landfill (GB16889-2008)," which stipulated that all landfill sites must self-treat the leachate. When the leachate meets the emission standards, they can be released into the municipal sewage treatment pipe network. This is a major challenge for the existing landfill sites. In the future, it is important to control the production of leachate and make full use of the landfill benefits, such as biogas and free land, to reduce landfill operating costs. Moreover, most of China's landfill sites are constructed based on an open field. Many landfill sites are small, lacking necessary facilities, and it is very difficult to upgrade them. This is completely different from the developed countries' method of planning before construction. So it is necessary for developing countries to conduct research, especially China.

The objectives of this study are as follows: 1) Establishing a suitable technical evaluation process for landfill upgrading, and evaluating the necessity and feasibility of upgrading the existing nine landfill sites in Nanjing, Jiangsu Province; 2) Assessing if "zoning planning," "rain and sewage diversion," and other technologies used in the Jiaozishan landfill site are effective to slow down the output and impact of leachate on the surrounding groundwater; 3) Integrating biogas and free land resources of the Jiaozishan landfill, and providing a low carbonization program for the future landfill operations.

2. Methods and Data

2.1. Research area

Nanjing is one of the three core cities in the Yangtze River Delta urban agglomeration, located at north latitude 31°14" to 32°37" and east longitude 118°22" to 119°14". Nanjing belongs to the subtropical humid monsoon climate, with an average annual temperature of 15.4 °C and an average annual rainfall of 1106.5 mm. In 2016, its total administrative area is 6597.2 km^2, among which the urban built area is 923.8 km^2. The total population is 8.236 million and the urban population is 6.704 million. The regional GDP of 2016 is $156.09 billion, and the per capita GDP is $19,000. The low hill and lake areas of Nanjing account for 60.8%, which provides an excellent location conditions for the landfill construction. Nanjing currently owns five regular landfill sites and four informal landfills. Nanjing has finished the long-term history of living garbage piled up randomly until 1993 due to the creation the national "health and civilization city". Three landfill sites were constructed to centralize process the living garbage, including Shuige, Jiaozishan, and Tianjingwa. In 2003, according to the relevant requirements issued by the state, the second stage of expansion projects were carried out on the Jiaozishan and Tianjingwa landfills using anti-seepage measures and the corresponding sewage treatment process. After 2004, the Tongjing and Ma'anshan landfills were built. The urban population of Nanjing has increased from 2.644 million to 6.704 million over the past 20 years, the amount of urban solid waste has increased from 0.884 million tons to 3.139 million tons, and the urban built-up area has expanded about four times. Additionally, the amount of household garbage that was directly scattered into the landfills before 1993 may be no less than 20 million tons. Not only does the growing output of municipal solid waste challenge the current landfill disposal capacity, it also contaminates the surrounding soil, water, and atmosphere, which accidentally forms urban waste "landscape scar" (Figure 1).

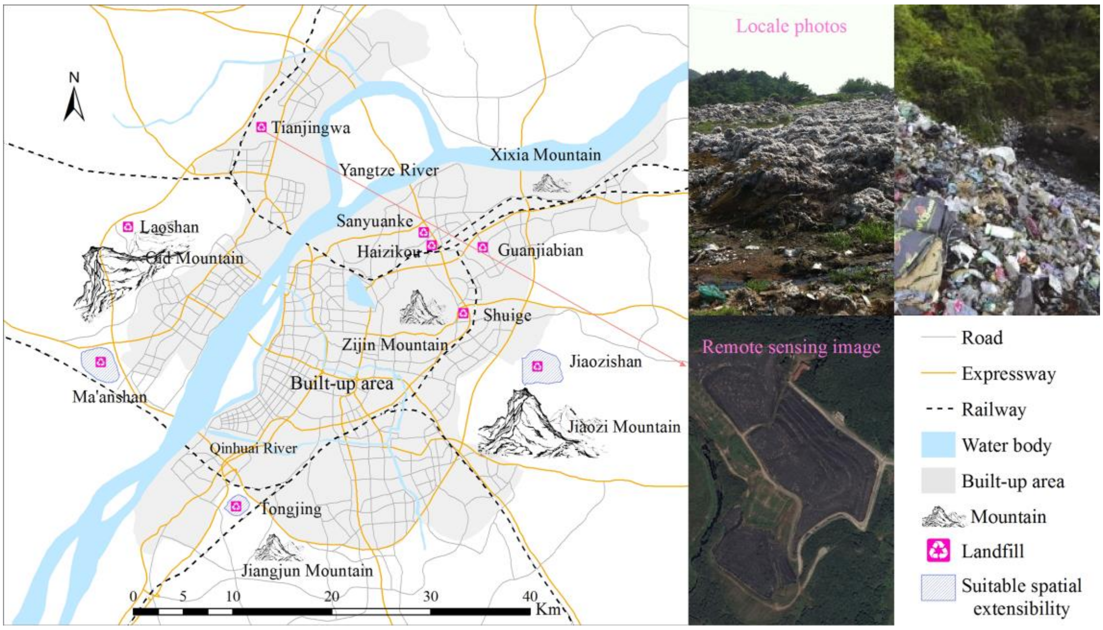

Fig. 1. Location and basic characteristics of the study area

2.2. Research methods

China's "construction standard of sanitary landfill for domestic waste" was issued in 2001, and it was revised in 2009 [20]. Since July 1, 2011, the State Environmental Protection Administration and the State Quality Supervision and Inspection Bureau of People's Republic of China have called for the execution of the new “Standard for Pollution Control of Domestic Refuse Landfill (GB16889-2008),” which stipulates that each existing municipal solid waste landfill should handle the landfill leachate on their own.

2.2.1. Research framework

A research framework for landfill reconstruction was formulated to effectively control the leachate production and outflow pollution, meet the national environmental protection requirements, reduce leachate treatment costs, and achieve energy-saving emission reduction targets (Figure 2). This research framework consists of four steps: (1) The AHP (analytic hierarchy process) model was used to reversely evaluate whether the locations of existing landfills were suitable [21]. Only landfills with appropriate location will be considered for the possibility of upgrade. (2) The public perceived value loss model was used to evaluate the total value loss that may result from upgrading the landfills, as well as to determine the feasibility of spatial extension of upgrading existing landfills [22]. (3) A reasonable zoning plan was conducted for landfill upgrading. The pre-landfill sites were executed for closure, while the arranged rain drainage system with the "rain and sewage shunt" method was used in long-term landfill sites, which could reduce the leachate output and slow down the effect of landfill leachate on the surrounding soil and groundwater environment. (4) To achieve low-carbon landfill operations in the future, it is important to make full use of biogas power generation of the landfill and use the free land to build photovoltaic power plants.

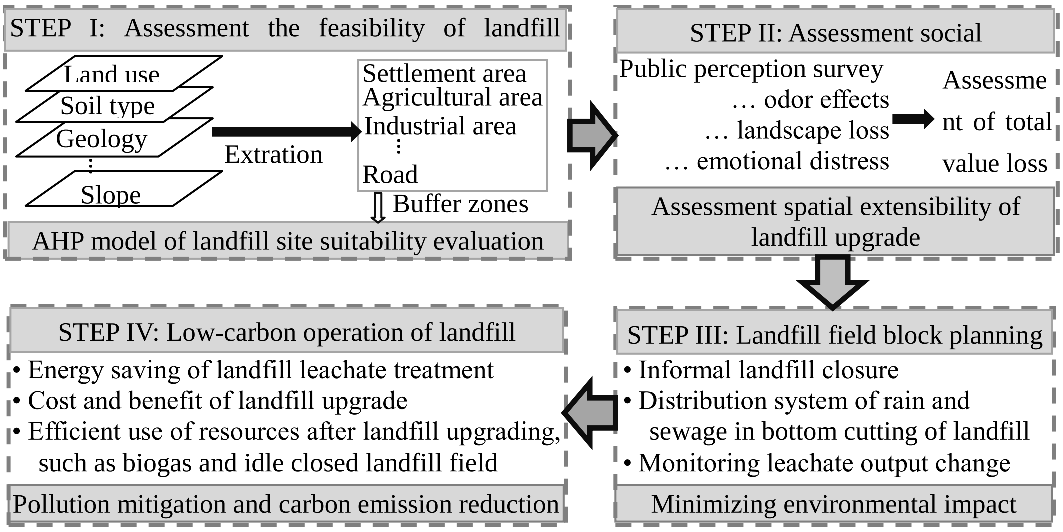

Fig. 2. Research framework for pollution mitigation and carbon emission reduction in this study

2.2.2. Leachate estimation

The "rain and sewage diversion" method at the bottom of the landfill can lead to a reasonable zoning planning of landfill while not reducing the landfill capacity. At the same time, separate rain water guide drainage facilities were set up for different blocks, which could separately guide the drainage between rain water of non-landfill area and landfill leachate, respectively. Then, the initial leachate output of the landfill and leachate treatment energy consumption would be reduced. Therefore, not only would this method alleviate the environmental risk of large amounts of leachate infiltration, but will also realize the reduction of CO_2 emissions from the landfill operation process [23]. The following empirical formula can be used to calculate the output of the landfill leachate:

$$Q = I \cdot \sum_{i=1}^{n} C_i A_i \tag{1}$$

Q represents the leachate output, I represents the average annual rainfall, n represents the blocks number of landfill partition, C_i represents the permeability coefficient of i bolck，A_i indates the catchment area of i bolck. C_i ranges from 0.1 to 0.8, which is affected by many factors, such as precipitation, evaporation, and the upper cover. According to the research of Yang et al. (2015) and CNS (Chinese National Standards, Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2008), the C_i values in Nanjing are 0.7、0.5、0.2、0.1 and 0.4, which correspond to landfill without cover, intermediate cover, unplanted final cover, planted final cover-intact, and planted final cover-defective, respectively [24,25]. I is constant, and C_i is the limited constant. Therefore, if Q is proportional to A_i, then the leachate output can be effectively reduced by using the zoning planning and "rain and sewage diversion " method to decrease A_i.

2.2.3. CO_2 emission reduction categories

Greenhouse gas (GHG) emission categories of the landfill can be divided into seven parts, including CO_2 emissions from waste collection and transportation, CO_2 emissions from landfill management, CO_2 emissions from leachate treatment, GHG emissions due to fugitive CH_4, saved CO_2 emissions as a substitution for electricity production, saved CO_2 emissions as carbons equestered in the landfill body and other GHG emissions, such as NO_2 and CO emissions [26]. The effects of landfill reconstruction on CO_2 emissions focus on CO_2 emissions from the leachate treatment and saved CO_2 emissions as a substitution for electricity production. Either the reconstruction has a little effect on CO_2 emission of the other parts, or the effect was so minimal it couldn't be accurately estimated.

In the first part, the CO_2 emission reduction effect was brought by the reduced leachate after closing the informal landfill over time and the transformation of regular landfill using the "rain and sewage diversion" method, resulting in a decrease in energy consumption of pollution treatment. First the reduced leachate output is calculated according to formula (1), then the Yang et al. (2013) method is used to go through the variable transformation and combine the previous empirical parameters, and the CO_2 emission reduction was finally calculated [26,27]. The specific formula is as follows:

$$C_{LT} = Q_r \times \sum_{i=1}^{n} \left(A_i \times EF_i \right) / 1000 \tag{2}$$

where C_{LT} represents the annual CO_2 emissions reduction from the leachate treatment (t); Q_r represents the volume of leachate generated from the annual landfill reduction (m^3); A_i represents the amount of the ith auxiliary material or energy used in the leachate treatment process（kg m^{-3} or kWh•m^{-3}"）; and EF_i represents the CO_2 emission factor for the provision of the ith auxiliary material or energy (kg kg^{-1} or kg kWh^{-1}), respectively。

Secondly, the biogas produced by the reformed landfill was utilized comprehensively, then the CH_4 escape amount was reduced, which lead to greenhouse gas effects. The available quantity of CH_4 converting into the equivalent CO_2 value could be caculated according to the formula listed by the IPCC Guidelines [28], the specific formula is as follows:

$$C_{SE} = P_{CH4} \times MCF \times \frac{24.5L \cdot mol^{-1}}{16g \cdot mol^{-1}} \times \beta \times \varepsilon \times LHV_{CH4} \times \gamma \times \frac{1}{3.6MJ \cdot kWh^{-1}} \times EF_e / 1000 \tag{3}$$

where C_{SE} represents the saved CH_4 emissions as substituted CO_2 emissions from electricity production (t); P_{CH4} represents the CH_4 potential of waste under anaerobic conditions, which is 36.3± 8.5 kg t^{-1} in this study [29]; MCF is the CH_4 conversion factor, which is 0.8 before 2016 and 1.0 after 2020 in this study [30]; ß represents the LFG collection efficiency, which is 50% in this study [31]; ε represents the CH_4 burnout rate, which is 95-99% in this study [32]; LHV_{CH4} represents the lower heating value of CH_4 under normal conditions (i.e. 101 kPa, 25°C, MJ m^{-3}), which is 37MJ m^{-3} in this study [32]; γ represents the energy recovery efficiency for the electricity generation from CH_4 combustion, which is 30% in this study; EF_e represents the CO_2 emission factor for the national power grid in China, which is 0.7035 kg kWh^{-1} in this study [26].

In the third part, the photovoltaic power plant will be built on the free land after the closure of some landfills, which can replace the fossil energy and realize the later low-carbon operations. According to the construction standard of China's thin film solar power station and the annual average sunshine time in Nanjing, the annual power generation capacity of the the solar power station is calculated by the substitution method and then converted to the CO_2 equivalent value. The calculation formula is as follows:

$$C_{solar} = A \times e \times h \times r \times EF_e \tag{4}$$

In the formula, C_{solar} indates the converted electricity CO_2 equivalent value, which is an alternative emission reduction potential; A indicates the available area of covered free land of the landfill (m^2, approximately 60% of the overlying free land can be used for photovoltaic power generation); e indicates the constructional photovoltaic power kilowatt hours per land area (1ha MW^{-1}, according to the design specification of photovoltaic power station and land control index of the photovoltaic power station project [33]); h indicates the annual sunshine time; r indicates comprehensive utilization coefficient (0.80); and EF_e, is the same as above.

2.3. Data investigation and processing

In January 2015, we were commissioned by the Nanjing Environmental Protection Bureau to carry out this research. Detailed information has been collected for each of the nine landfills, such as storage capacity, landfill, and leachate treatment. Additionally, the groundwater quality data of monitoring the wells in the Jiaozishan landfill was collected. In February and August of 2015, the Jiaozishan landfill leachate collection tank, monitoring wells, surrounding agricultural wells, and drilling borehole water samples were also collected, processed, and analyzed according to NSPRC 1989 and Du et al. (2005) [34,35]. The 1: 10000 Land use map, 1: 50000 Geological map, soil type chart, QuickBird remote sensing image of July 29, 2015 (resolution 0.61m), and other information was collected from the Land Resources Bureau. The AHP and perceived value loss calculation models were both constructed based on the results of related research. The SPSS19.0 software was used to analyze the data and correlate the analysis. The ARCGIS10.2 software was used to perform the overlay and buffer analysis of land use, soil type, geology, hydrology, and road distance.

3. Results

3.1 The dual pressures of environmental protection and treatment capacity

As there was no strict standard for landfill construction in China until 2001, the Shuige, Jiaozishan and Tianjingwa landfills constructed in 1993 belonged to the controlled landfill. It was difficult for their engineering measures to meet the requirement for environmental protection. After the second transformation phase in 2003, the Tongjing and Jiaozishan landfills were later constructed as the sanitary landfills. The four informal landfills formed in history belonged to the decay typical landfill, which seriously threatened the ecological environment of the surrounding areas. Moreover, the city's solid waste has a high organic content, easily harming the groundwater and soil (Table 1).

Figure 3a shows the increasing trend from 1984 to 2016 of municipal solid waste in Nanjing, with the amount reaching 3.139 million tons. The Environmental Protection Bureau of Nanjing has predicted that the amount of municipal solid waste would reach 3.63 and 4.85 million tons in the years 2020 and 2030, respectively [36]. The the continued growth of the city population and GDP was the primary reason for the sustainable growing city solid waste. The city population and GDP of Nanjing have increased from 2.2075 million in 1984 and 6.582 billion Yuan in 2016 to 6.704 million and 1050.3 billion Yuan, which is an increase of 304% and 15957%, respectively [37]. There was a significant positive correlation between the urban population and the amount of solid waste products, while urban GDP was positively correlated with waste output (Figure 3 b, c).

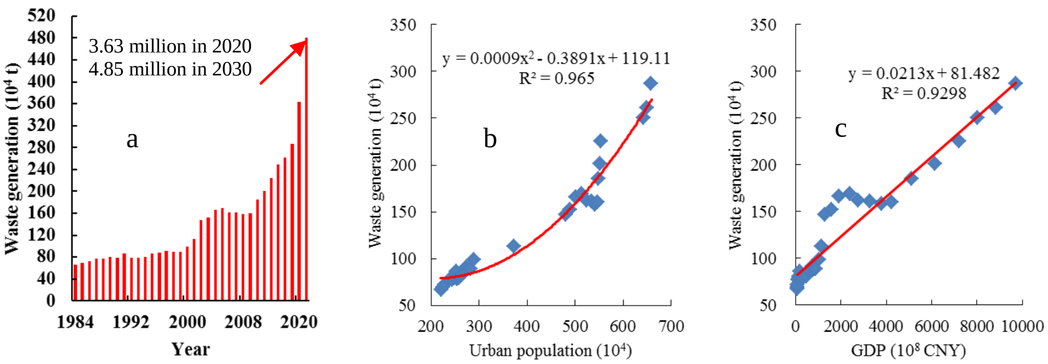

Fig. 3. The growth of municipal solid waste and its correlation with population and GDP in Nanjing

The incineration treatment accounted for less than 10% and the direct disposal was about 6% for the Nanjing municipal solid waste; the remaining municipal solid waste eventually tended to the landfill [38]. However, unlike transportation, electricity, and water supply, the construction and planning of the landfill has not yet received government attention. Moreover, an overtime of work was still required to deal with the rapid growth of the city garbage output even if the landfills did not comply with current environmental standards. Therefore, it is imperative to rebuild and upgrade the existing landfills.

Table 1. Properties of MSW in Nanjing City, China

	Food	Wood	Paper and cardboard	Plastic	Textile	Glass	Metal	Fines	Stones and brick	Total
Physical properties										
Wet weight fraction (%)	46.2	2.3	12.6	7.2	6.4	1.6	1.1	21.7	3.2	100
Moisture content (%)	64.2	44.3	27.8	34.2	37.2	7.8	6.4	14.3	9.4	40.4
Dry weight fraction (%)	16.5	1.3	9.1	4.7	4.0	1.5	1.0	18.6	2.9	59.6
Chemical properties – ultimate analysis (Wet basis)										
C_{org} (%)	48	47.8	43.5	0	55	0	0	1.5	0	31.5
C_{iorg}(%)	0	0	0	60.0	0	0.5	4.5	2.5	1.8	5.0
H (%)	6.4	6.0	6.0	22.7	6.6	0.1	0.6	0.4	0.2	5.9
O (%)	37.6	38	44.2	7.2	31.2	0.4	4.3	3.5	3.2	26.4
N (%)	0.4	0.3	0	0.1	4.3	0	0	0.8	0.4	0.7
S (%)	2.6	3.4	0.3	0	0.4	0.1	0.2	1.2	0.2	1.6
Ash (%)	5.0	4.5	6.0	10.0	2.5	98.9	0.4	90.1	94.2	28.1

3.2 Feasibility analysis of landfill upgrade

The AHP model was used to anti-evaluate the feasibility of upgrading nine landfills in Nanjing. The results showed that only three of the five regular landfills could continue upgrading, while Tianjingwa and Shuige have been surrounded by the city due to the expansion of city built area. They were not suitable as the landfill and should be immediately closed. Only the Laoshan landfill was suitable for upgrading among the four non-formal landfills, whereas the other three did not meet the basic upgrading conditions.

Table 2. The evaluation results of upgrading feasibility of 9 landfills in Nanjing

Limiting factor	Limiting sub-factor	QLS	TJ	TJW	SG	MAS	LS	HZK	GJB	SYK
environmental geological factor	Topography conditions	5	3	5		5	5	3	5	5
	Site stability	5	5		5	5	5	5	5	5
	Distance from water source	5	3	5	3	5	5	3	3	3
	Bottom cohesive soil thickness	5	5	5	5	5	5	5	3	5
	Sidewall cohesive soil thickness	3	5	3	5	5	3	5	3	5
	Permeability of cohesive soil	3	5	3	3	5	5	5	5	5
	Groundwater depth	5	3	3	3	3	5	3	3	3
Environmental protection factors	Distance from surface water	5	3	5	1	3	5	1	3	1
	Distance from settlements	3	3	×	×	5	5	×	×	×
	Distance from town	5	5	×	×	5	5	×	×	×
	Distance from industrial area	3	3	×	3	3	3	×	×	×
Traffic and transportation conditions	Distance from existing highway	5	5	5	5	5	5	5	5	5
	Garbage transport distance	5	3	5	5	3	3	5	5	5
Social environmental impact	Distance from scenic area	5	5	5	3	5	1	3	3	3
	Distance from railway	3	5	3	3	5	5	1	×	3
	Distance from airport	5	5	5	5	5	5	5	5	5
	Population number within 1000 meter	5	3	×	1	5	5	×	×	×
	Population number within 1500 meter	5	3	×	1	3	5	×	×	×
	Population number within 2000 meter	3	3	×	3	3	5	×	×	×
Comprehensive evaluation results		feasible	feasible	unfeasible	unfeasible	feasible	feasible	unfeasible	unfeasible	unfeasible

Notes: scoring criteria: completely suitable--5points, generally suitable--3points, limited suitable--1 point, completely unsuitable --×, once there is completely unsuitable, the comprehensive result is unfeasible.

3.3 Influence of landfill reconstruction on Leachate Pollution

The Jiaozishan landfill has the largest daily waste treatment capacity in Nanjing (2,600 tons per day). Its waste treatment capacity has been 1200 tons per day since it was opened in 1993, and it has accumulated a landfill of 4.7 million m^3 until 2011. In 2003, the 120,000 square meters of phase I have carried out the implementation of the anti-seepage transformation. Additionally, the 160,000 square meter phase II construction started. In 2008, the 84,000 square meters of the first phase implemented the planted final cover-defective. In order to cope with the continuous growth of urban solid waste in Nanjing, the Jiaozishan landfill started the phase III project in 2011 with an expansion of 170,000 square meters; the service extended to 2030.

3.3.1 Effects of the implementation of zoning plan of "rain and sewage diversion" at the bottom of the Jiaozi Mountain landfill on the leachate production

Since the new "Standard for Pollution Control of Domestic Refuse Landfill (GB16889-2008)" was implemented on July 1, 2011, the Jiaozishan landfill itself was very large. The costs of the leachate collection and treatment are very large if the scientific division is not carried out. Therefore, phase III project has implemented the "rain and sewage diversion" zoning plan as follows: first, improve the incomplete planted final cover-defective to the planted final cover-intact of 84,000 square meters in the phase I project; second, accelerate the landfill work of the remaining area of the phase I project, and implement all closure of the phase I project in 2014; third, complete 68,000 square meters of covered landfill area of the phase II project, and carry out no planting coverage; fourth, divide the remaining 92,000 square meters of the phase II project into two blocks, construct the 44,000 square meters as untreated landfill area, and take the 48,000 square meters to be landfill implementing "rain and sewage diversion". The 170,000 square meters of phase III project were divided into four blocks. No treatment is created from the 45,000 square start areas, while the remaining 125,000 square meters are divided into three pieces to carry out the "rain and sewage diversion" plan. As shown in table 3, the "rain and sewage diversion" zoning plan could effectively control the leachate output. Compared with the data in 2011, the landfill in 2015 has expanded to 60.7% while the actual leachate output decreased by 30.8%. If the zoning planning has not been implemented, the possible maximum leachate output would be 124.7% higher than the actual output. The actual leachate output correlates with the theoretical leachate output ($p=0.01$), and the Pearson correlation coefficient was about 0.9745. All of these results showed that the zoning plan was scientific and reasonable.

3.3.2. Mitigation of leachate pollution by landfill reconstruction

The physicochemical indexes of leachate infiltration are various. To conduct the comparing analysis for the simplified expression, we chose the COD, TN, Cl^-, and Cr. On the other side, they represented the inherent stability of organic and inorganic compounds and heavy metals [39]. The Jiaozishan landfill daily water quality monitoring data and borehole sampling analysis results in February and August of 2011 and 2016 are shown as follows (Figure 4): the COD, TN, Cl^-, and Cr contents were highest in the leachate collection pond, the index of landfill surrounding monitoring well just followed, while the index in the surrounding agricultural well water and borehole water sampling were the lowest. Compared with 2011, the COD content changed the most in 2016, and the decline rate was up to 17.6%. The changes of other indicators were relatively small, but the overall index in 2016 was better than in 2011. These results implied that with the improvement of the coverage and zoning planning, the reconstruction of the Jiaozishan landfill site has effectively alleviated the pollution of landfill leachate to the surrounding groundwater.

Table 3. The variation and forecast of leachate output before and after reconstruction of the Jiaozishan landfill

year	Annual rainfall (mm)	Total area ($10^4 m^2$)	Coverage status of landfill site						The maximum possible leachate production without the zoning plan	Theoretical leachate production (m^3)	Actual leachate production (m^3)
			A	B	C	D	E	F			

									zoning plan (m^3)		
2011	1077.0	28		19.6		0	0	8.4	183951.60	183951.6	174436.2
2012	917.2	28		16	3.6			8.4	150053.92	150053.92	161245.4
2013	898.4	45		33	3.6		8.4		231248.16	231248.16	237389.5
2014	1091.1	45	4.8	21.4	6.8	3.6	8.4		254226.30	217565.34	223246.8
2015	1765.6	45	17.3	8.9		6.8	12	0	369010.40	155196.24	164247.3
2020	1106.5	45	12.5	8.5		5.2	18.8		194965.3	98146.55	
2030	1106.5	45					45		49792.5	49792.5	

Note: A-- rain and sewage diversion area, B-- uncovered area, C-- intermediate cover, D-- unplanted final cover, E-- planted final cover-intact, F-- planted final cover-defective

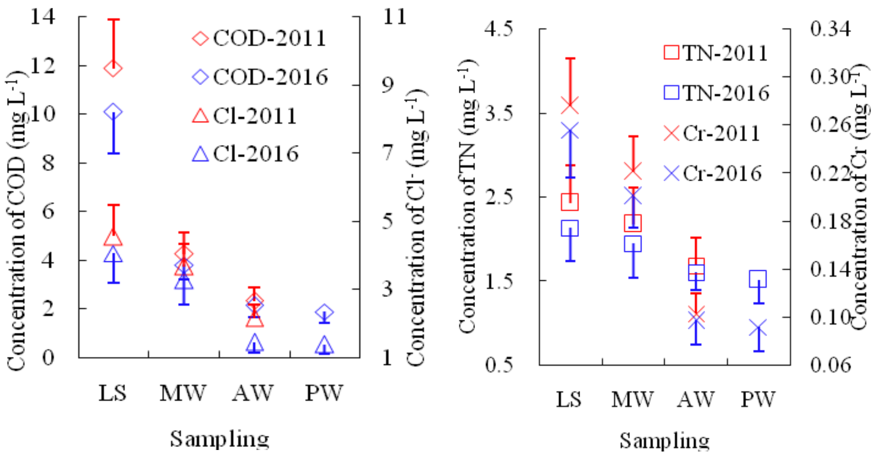

Fig. 4. Changes of physicochemical characteristics of landfill leachate before and after reconstruction

Notes: LS stands for leachate sumps, n=4 samples×2 periods; MW stands for monitoring well, n=8 samples ×2 periods; AW represents agricultural well, n=5 samples ×2 periods; PW represents pore water, n=11 samples ×2 periods. The values in the figure are average, and the error column stands for standard deviation (the positive or negative semi variance of 2011 and 2016 are shown for clear).

3.4 Effect of landfill reconstruction on CO_2 emission reduction

According to formulas 2, 3, and 4, the contributions of reduced leachate production caused by the landfill reconstruction, biogas power generation replacing fossil energy, and overlying free photovoltaic power generation to CO_2 emission reduction were each calculated, respectively. Figure 5 showed that not only did the landfill reconstruction reduce leachate output in 2015, but it also collected the biogas from sealing the areas of phase I and II, and built a solar power station on the free land. At first, the annual CO_2 emissions were about 55,000 tons, and the CO_2 emission reduction each year after 2030 might reach about 86,000 tons. The effect of in the initial stage of CO_2 emission reduction brought by the leachate treatment was good. However, with the gradual closure of the landfill site, the area of rainwater diversion at the bottom of the field was reduced, and there was not an obvious role of zoning. The Jiaozishan landfill was very large with many closed staging blocks, which could provide the stable sources of biogenic gas; this was also important for biological gas power and CO_2 emission reduction. After the closure of the garbage landfill, the benefits brought by the construction of thin film solar power station were shown as follows: first off, free land resources were effectively used; secondly, it eased the lack of space available for big city construction; third, a solution of low carbon and sustainable management for landfill operation was provided, also to achieve CO_2 emission reduction and alleviate government's financial pressure. Not considering the right of carbon trading, the photovoltaic electric tariff charged up to 20-40 million CNY, which could completely meet the funding requirement of the daily landfill operation and management.

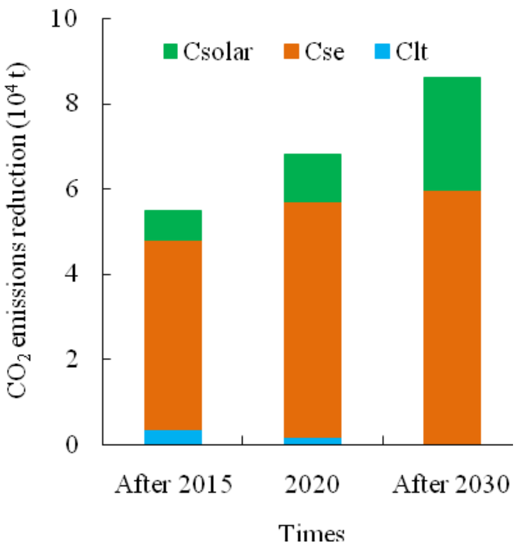

Fig. 5. The contribution of landfill reconstruction to the future CO_2 emission reduction

4. Discussion

The municipal solid waste treatment Nanjing was relatively simple, and 84% of the garbage needed the landfill treatment. In fact, Nanjing is located in the eastern coastal areas, and its land resources were scarce. People greatly resisted the site selection of the incineration plant although the incineration treatment was a more appropriate method [40]. Previous studies have shown that incineration could greatly reduce the landfill volume with lower CO_2 emissions [29, 30, 41]. The Chinese government has set the goal for the proportion of incineration of municipal solid waste to reach 30% by 2030 [42]. Nanjing vigorously develops the incineration treatment to alleviate the pressure of landfill treatment. Like most cities in China, the informal landfills in Nanjing have been responsible for the disposal of municipal solid waste. Also the pollution of these landfills to the surrounding environments are beyond a doubt, and the unique remedial measure is to upgrade or close them as soon as possible. Therefore, it is necessary to assess the feasibility of landfill upgrading, and the previous location research principle is still effective. The AHP model of reverse evaluation was used in this paper, and the evaluation results were fitting with the actual situation. Because the public has considered the reconstruction of the landfill site, the public resentment and perceived value resulted from landfill reconstruction were minimized [22].

Municipal solid waste is an important carbon source; its recycling and emission reduction potential has always been a research hotspot [43-46]. This study showed that, contrary to fossil energy, biogas power generation can reduce 45,000-60,000 tons of CO_2 emissions per year. Considering the time cycle of gas production, the CO_2 emission reduction of the biogas power generation from the Jiaozishan landfill accounted for 33.2-44.3% of the total CO_2 emission of the entire urban solid waste. This ratio is slightly lower than the proportion of 40-60% CO_2 emission reduction in China's landfill gas generation alternative to fossil fuels that was estimated by Yang al. (2013), while it is higher than that in some other developing countries [26, 30]. In fact, the proportion of CO_2 emissions from incineration of solid waste is higher, and the proportion of some countries has reached up to 80% or higher [47]. The incineration treatment should be vigorously promoted, even if only from the perspective of CO_2 emission reduction. Local governments should focus on environmental protection measures of incineration power generation and guide the public to be convinced of its benefits. The operation and management of the closed landfill is another important problem [48]. The country has primarily used general overlying free land of closed landfills as country parks. However, the utilization rate of these country parks with poor location, poor security, poor public psychological conflict, and higher operating costs are extremely low, leading them to become a long-term financial burden for the government. This causes them to attract public criticism. Meanwhile, the available land resources for the construction of Nanjing are relatively scarce. Therefore, after the stepping closure of the Jiaozishan landfill, building a film solar power station should be a priority for the overlying free land. The comprehensive closed field can be estimated to be built for a 30MW photovoltaic power station in 2030, which is equivalent to an annual reduction of 26,000-30,000 tons CO_2. At the same time, the photovoltaic power station can generate 20-40 million CNY from the annual electricity sales, which could fund nearly 20 years of continuous operation and management of the landfill after the closure, which is also very attractive to the government policy makers.

5. Conclusion

As China's environmental standards for the waste landfill has become more and more strict, many informal landfill sites cannot meet the requirements of environmental protection. In this study, a technical process applicable for the landfill upgrading in China was established. On the basis of insitu investigations, the analytic hierarchy process model was used to evaluate nine landfill sites in Nanjing city. The results showed that just four landfills were suitable for upgrading and reconstruction. After the technical reconstruction of the Jiaozishan landfill using the bottom rain sewage diversion "zoning planning,” the landfill scale has expanded 60.7%, while the actual amount of leachate output has been reduced by 5.84%. The maximum theoretical leachate output was 124.7% higher than the actual output. Contrary to fossil fuels, biogas can achieve a CO_2 emission reduction of 45,000-60,000 tons, which accounted for approximately 33.2-44.3% of CO_2 emissions from the total municipal solid waste. The free land of the closed landfill can be used to build a photovoltaic power station, which could not only reduce 26,000-30,000 tons of CO_2 emissions, but can also generate 20-40 million CNY per year from the selling of electricity. Each of these will be beneficial in alleviating the continuous financial pressure after the landfill closure.

Acknowledgements

The authors would like to gratefully acknowledge the research grants from the Fundamental Research Funds for the Central Universities (2017XKQY070). In addition, the authors would like to thank Bureau of Land and Resources of Nanjing City for the support during the research.

References

[1] Ali, M.: Editorial: urban waste management as if people matter. Habitat Inter. 30, 729-730 (2006).

[2] Hoornweg, D., Bhada-Tata, P., Kennedy, C.: Environment: Waste production must peak this century. Nature. 502(7473), 615-617 (2013).

[3] NSBC: China urban Statistical Yearbook. National Bureau of Statistics of China. http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm (2016).

[4] Zaman, A.U., Lehmann, S.: Urban growth and waste management optimization towards ‘zero waste city’. City Cult. Soc. 2, 177-187 (2011).

[5] Hird, M.: Waste, Landfills, and an Environmental Ethic of Vulnerability. Ethics Environ. 18, 105-124 (2013).

[6] Han, H.Y. , Zhang, Z.J., Xia, S.: The Crowding-Out Effects of Garbage Fees and Voluntary Source Separation Programs on Waste Reduction: Evidence from China. Sustainability. 8(7), 678, doi:10.3390/su8070678 (2016).

[7] Han, H.Y. , Zhang, Z.J.: The impact of the policy of municipal solid waste source-separated collection on waste reduction: a case study of China, J. Mater. Cycles Waste Manag. 19(1), 382–393 (2017).

[8] Wang, Y., Cheng, K., Wu, W.D., Tian, H.Z., Yi, P., Zhi, G.R., Fan, J., Liu, S.H.: Atmospheric emissions of typical toxic heavy metals from open burning of municipal solid waste in China. Atmospheric Environ. 152, 6–15 (2016)

[9] Chan, J.: The ethics of working with wicked urban waste problems: The case of Singapore's Semakau Landfill. Landscape Urban Plan. 2016, 123-131(2016).

[10] Zhang, X., Matsuto, T.: Assessment of internal condition of waste in a roofed landfill. Waste Manage. 33, 102-108 (2013).

[11] Reichert, A., Small, M., Mohanty, S.: The impact of landfills on residential property values. J. Real Estate Res. 7, 297-314 (1992).

[12] Mor, S., Ravindra, K., Dahiya, R.P., Chardra, A.: Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site. Environ. Monit. Assess. 118, 435–456 (2006).

[13] Reyes-Lópeza, J.A., Ramírez-Hernándeza, J., Lázaro-Mancilla, O., Carreón-Diazcontia, C., Garrido, M.M.: Assessment of groundwater contamination by landfill leachate: A case in México. Waste Manage. 28, S33–S39 (2008).

[14] Vrijheid, M.: Health effects of residence near hazardous waste landfill sites: a review of epidemiologic literature. Environ Health Perspect. 108, 101-112 (2000).

[15] Adamcová, D., Vaverková, M.D., Bartoň, S., Havlíček, Z., Břoušková, E.: Soil contamination in landfills: a case study of a landfill in Czech Republic. Solid Earth. 7, 239-247 (2016).

[16] Panchoni, L.C., Santos, C.A., Kuwano, B.H., Carmo, K.B., Cely, M.V., Oliveira-Júnior, A.G., Fagotti, D.S., Cervantes, V.N., Zangaro, W., Andrade, D.S., Andrade, G., Nogueira, M.A.: Effect of Landfill Leachate on Cereal Nutrition and Productivity and on Soil Properties. J. Environ. Qual. 45, 1080-1086 (2016).

[17] Zaman, A.U.: Comparative study of municipal solid waste treatment technologies using life cycle assessment method, Int. J. Environ. Sci. Technol. 7, 225–234 (2010).

[18] Idris, A., Inanc, B., Hassan, M.N.: Overview of waste disposal and landfills/dumps in Asian countries. J. Mater. Cycles Waste Manag. 6, 104-110 (2004).

[19] Zhang, D.Q., Tan, S.K., Gersberg, R.M.: Municipal solid waste management in China: Status, problems and challenges. J. Environ. Manage. 91, 1623-1633 (2010).

[20] Ministry of Construction Development of the People's Republic of China: Technical Code for domestic waste sanitary landfill engineering construction (124-2009). Chinese Industrial Standard. China Architecture & Building Press, Beijing, China (in Chinese) (2009).

[21] Şener, Ş., Şener, E., Nas, B., Karagüzel, R.: Combining AHP with GIS for landfill site selection; A case study in the Lake Beys¸ ehir catchment area (Konya, Turkey). Waste Manage. 30, 2037-2046 (2010).

[22] Chen, F., Luo, Z.B., Yang, Y. J., Lü, J., Liu, G. J., Ma, J.: Designing E-waste landfill as a landscape

infrastructure: A case study based on public perceptions in Nanjing, China. IWWG-ARB, Seoul, Korea (2017).

[23] Albright, W.H., Benson, C.H., Gee, G.W., Roesler, A.C., Abichou, T., Apiwantragoon, P., Lyles, B.F., Rock, S.A.: Field water balance of landfill final covers. J. Environ. Qual. 33, 2317-2332 (2004).

[24] Yang, N., Damgaard, A., Kjeldsen, P., Shao, L.M., He, P.J.: Quantification of regional leachate variance from municipal solid waste landfills in China. Waste Manage. 46, 362-372 (2015).

[25] Ministry of Housing and Urban-Rural Development of the People's Republic of China: Technical Code for domestic waste sanitary Landfill pollution control (GB16889-2008). Chinese National Standard. China Planning Press, Beijing, China (in Chinese) (2008).

[26] Yang, N., Zhang, H., Shao, L.M., Lü, F., He, P.J.: Greenhouse gas emissions during MSW landfilling in China: influence of waste characteristics and LFG treatment measures. J. Environ. Manage. 129, 510–521 (2013).

[27] HWEC (Hehai Water Environmental Company): Technology Design of Leachate Treatment Plant in Wanshan Landfill Site (2005).

[28] IPCC (Intergovernmental Panel on Climate Change): 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change. Geneva, Switzerland (2006).

[29] Yang, N., Zhang, H., Chen, M., Shao, L.M., He, P.J.: Greenhouse gas emissions from MSW incineration in China: Impacts of waste characteristics and energy recovery. Waste Manage. 32, 2552-2560 (2012).

[30] Tan, S.T., Hashim, H., Lim, J.S., Ho, W.S., Lee, C.T., Yan, J.: Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia. Appl. Energy. 136, 797-804 (2014).

[31] Wanida, W., Shabbir, H.G.: Life cycle assessment as a decision support tool for landfill gas-to energy projects. J. Clean. Prod. 15, 1819-1926 (2007).

[32] Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H.: Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Manage. Res. 27, 825-836 (2009).

[33] Ministry of Housing and Urban-Rural Development of China: Technical code for photovoltaic power station design (GB50797-2012). Chinese Industrial Standard. China Architecture & Building Press, Beijing, China (in Chinese) (2012).

[34] NSPRC (National Specifications of the People's Republic of China): Water quality determination of the chemical oxygen demand-dichromate method GB 11914-89. China Standard Press, Beijing, China (in Chinese) (1989).

[35] Du, Y.J., Hayashi, S., Liu, S.Y.: Experimental study of migration of potassium ion through a two-layer soil system. Environ Geol. 48, 1096–106 (2005).

[36] EPA: http://www.njhb.gov.cn/43168/43169/201507/t20150731_3488173.html (2015).

[37] NSBC: China Statistical Yearbook. National Bureau of Statistics of China. http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm (2016).

[38] NEPB (Nanjing Environmental Protection Bureau): http://www.njhb.gov.cn/43322/43328/201606/t20160606_3970612.html (2016)

[39] Zhan, T.L.T., Guan, C., Xie, H.J., Chen, Y.M.: Vertical migration of leachate pollutants in clayey soils beneath an uncontrolled landfill at Huainan, China: A field and theoretical investigation. Sci. Total Environ. 470–471, 290–298 (2014).

[40] Li, Y., Koppenjan, J.F.M., Verweij, S.: Governing Environmental Conflicts in China: Under what Conditions do Local Governments Compromise? Public Administration: An International Quarterly, 94, 806-822 (2016).

[41] Pan, S.Y., Du, M.A., Huang, I.T., Liu, I.H., Chang, P.C.: Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. J. Clean. Prod. 108, 409–421 (2015).

[42] Zheng, L.J., Song, J.C., Li, C.Y., Gao, Y.G., Geng, P.L., Qu, B.N., Lin, L.Y.: Preferential policies promote municipal solid waste (MSW) to energy in China: Current status and prospects. Renew. Sust. Energ. Rev. 36, 135–148 (2014).

[43] Lohila, A., Laurila, T., Tuovinen, J.P., Aurela, M., Hatakka, J., Thum, T., Pihlatie, M., Rinne, J., Vesala, T.: Micrometeorological measurements of methane and carbon dioxide fluxes at a municipal landfill. Environ. Sci. Technol. 41, 2717-2722 (2007).

[44] Johari, A., Saeed, I. A., Hashim, H., Alkali, H., Ramli, M.: Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. Renew Sustain. Energy Rev. 16, 2907-2912 (2012).

[45] Zuberi, M.J.S., Ali, S.F.: Greenhouse effect reduction by recovering energy from waste landfills in Pakistan. Renew. Sust. Energ. Rev. 44, 117-131 (2015).

[46] Liu, Y.L., Ni, Z., Kong, X., Liu, J.G.: Greenhouse gas emissions from municipal solid waste with a high organic fraction under different management scenarios. J. Clean. Prod. 147, 451–457 (2017).

[47] Arafat, H.A., Jijakli, K., Ahsan, A.: Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. J. Clean. Prod. 105, 233-240 (2015).

[48] Panepinto, D., Senor, A., Genon, G.: Energy recovery from waste incineration: economic aspects. Clean Technol. Envir. 18, 517-527 (2016).