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Approach of technical decision-making by element flow analysis and Monte-Carlo simulation of municipal solid waste stream

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Abstract

This paper deals with the procedure and methodology which can be used to select the optimal treatment and disposal technology of municipal solid waste (MSW), and to provide practical and effective technical support to policy-making, on the basis of study on solid waste management status and development trend in China and abroad. Focusing on various treatment and disposal technologies and processes of MSW, this study established a Monte-Carlo mathematical model of cost minimization for MSW handling subjected to environmental constraints. A new method of element stream (such as C, H, O, N, S) analysis in combination with economic stream analysis of MSW was developed. By following the streams of different treatment processes consisting of various techniques from generation, separation, transfer, transport, treatment, recycling and disposal of the wastes, the element constitution as well as its economic distribution in terms of possibility functions was identified. Every technique step was evaluated economically. The Mont-Carlo method was then conducted for model calibration. Sensitivity analysis was also carried out to identify the most sensitive factors. Model calibration indicated that landfill with power generation of landfill gas was economically the optimal technology at the present stage under the condition of more than 58% of C, H, O, N, S going to landfill. Whether or not to generate electricity was the most sensitive factor. If landfilling cost increases, MSW separation treatment was recommended by screening first followed with incinerating partially and composting partially with residue landfilling. The possibility of incineration model selection as the optimal technology was affected by the city scale. For big cities and metropolitans with large MSW generation, possibility for constructing large-scale incineration facilities increases, whereas, for middle and small cities, the effectiveness of incinerating waste decreases.

Key words: municipal solid waste; element stream analysis; Monte-Carlo method; technical decision-making

Introduction

China generated 148 million tons of municipal solid waste (MSW) in 2003 with an annual increase rate of 5%–9% over the last 20 years (Wang, 2005). Many kinds of technologies are available such as landfilling, composting, incineration, recycling (Chung and Poon, 1998; Boyle, 2000; Małgorzata, 2001; Zhang *et al*., 2003). In order to treat and dispose of MSW properly and economically in an environment friendly manner, it is needed to study carefully the technology before application. For one reason, the treatment and disposal of different MSW demand various technologies due to the variety of the nature, amount and composition of MSW in different cities (He *et al*., 2003). For the other, every technology has its application conditions and limitations because of its own advantages and disadvantages (Hou and Ma, 2005). Therefore, it is not a scientific way to select a technology without detailed technical support (Wang and Nie, 2001).

Nowadays, more facilities of MSW treatment and disposal are in a great demand because of the pressure from solid waste pollution (Zhao and Lu, 2001). As a result, it is an urgent question how to choose the most appropriate technology to construct the corresponding facilities. Currently, it is in general random, subjective and nonscientific to choose the MSW treatment and disposal technologies. This has contributed to malfunction of numerous facilities, or resulted in the great waste of facilities because the technologies did not match the practical conditions of the reality.

Therefore, the clearly-outlined technological policy of MSW treatment and disposal is timely and greatly needed. The current technological policy is still limited to its preliminary phase without sound theoretical backup. Consequently, some researchers have dedicated themselves to studying and developing programming models on MSW management (Chang and Nishat, 2005). While still it has been urgent task to simulate a simple, reliable, practical model to analyze the technologies of MSW treatment and disposal and thus provide robust technical support to policy-making.

The objective of this study was to integrate various treatment and disposal technologies and analyze the elements stream of MSW. C, H, O, N, S were pickup and analyzed in this study, because they are the five major elements contained in MSW. A Monte Carlo mod-

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el, which combined Analytic Utility Process, Analytic Hierarchy Process, Analytic Uncertainty Process and Analytic Information Integration Process, was constructed and simulated. Every technological step was evaluated economically. The key technologies of MSW treatment and disposal were identified and estimated under designed conditions and the optimal treatment and disposal system was selected in terms of economical and technological perspectives. The final destination of C, H, O, N, S within the best technological system was calculated. Finally, a set of procedures and methodologies were offered to choose the optimal treatment and disposal technological system of MSW, which can be used to provide practical and effective technical support to the policy-making in China.

1 Methodology

1.1 Selection of MSW

Since the objective of this study was to support the policy making for proper MSW disposal in China, typical MSW was used in this study instead of those from a specific city (Nie, 2000) (Table 1).

Table 1 Typical composition of MSW in China

Composition	Weight (%)	Elemental percentage by weight (%)				
		C	H	O	N	S
Wood	2	49.5	6.0	42.7	0.2	0.1
Yard waste	12	47.8	6.0	38.0	3.4	0.3
Dirt, ash etc.	4	26.3	3.0	2.0	0.5	0.3
Plastics	3	60.0	7.2	22.8	0.0	0.0
Rubber	0.5	78.0	10.0	0.0	2.0	0.0
Paper	15	43.5	6.0	44.0	0.3	0.2
Cardboard	4	44.0	5.9	44.6	0.3	0.2
Textiles	2	55.0	6.6	31.2	4.6	0.15
Leather	0.5	60.0	8.0	11.6	10.0	0.4
Food waste	45	48.0	6.4	37.6	2.6	0.4
Other metal	1	0.0	0.0	0.0	0.0	0.0
Tin cans	1	0.0	0.0	0.0	0.0	0.0
Glass	8	0.0	0.0	0.0	0.0	0.0
Ferrous metal	2	0.0	0.0	0.0	0.0	0.0
Total	100	41.253	5.414	32.164	1.811	0.273

1.2 MSW stream

In this study, MSW stream is defined as the transfer and transformation of the component of municipal solid waste during the processes of production, transportation, treatment and disposal which includes the ingredient of municipal solid waste, the methods of treatment and disposal, the conversion of the component and its final

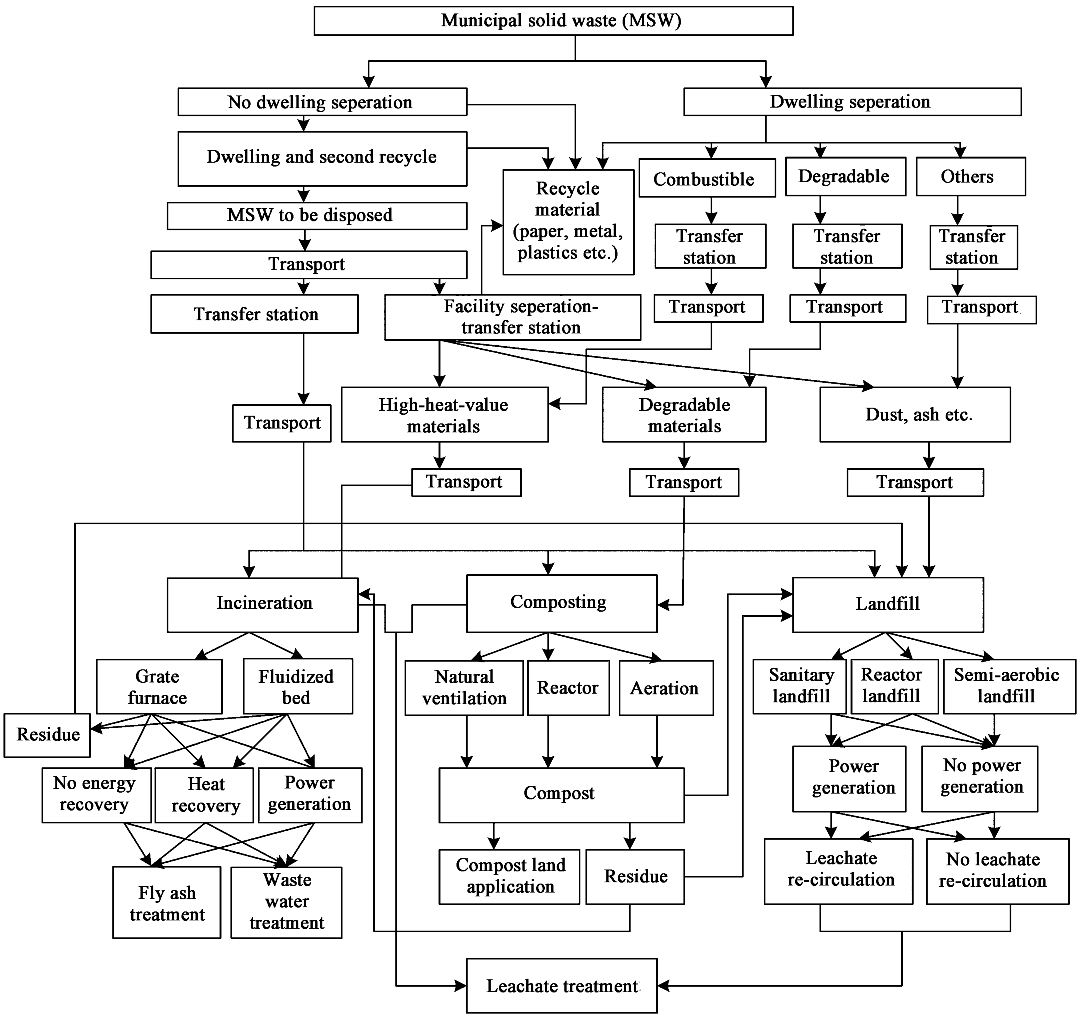

Fig. 1 Treatment and disposal technologies system of MSW.

constitution in environment. The techniques to treat and dispose MSW include landfill, composting, incineration, recycle and pre- and post-treatment. Each technique involves many kinds of facilities and various equipments, which produces various economic and environmental impacts. In this study, all the most frequently used equipments of each technology were identified and summarized in Fig.1. Every step of the MSW stream for each technology was economically analyzed and summarized (Table 2).

The recyclable compositions of MSW include plastic, rubber, paper, cardboards, textiles, leather, tin cans, glass, ferrous metals and other metals. The recycle percentage and price of different compositions varies with their components and natures. The recycle prices and percentages are shown in Table 3.

2 Modeling

Based on the aims of innocent and recovery of C, H, O, N and S of MSW, the economy of all the treatment modes

Table 2 Economical analysis of MSW treatment/disposal technologies

Treatment/disposal technologies				Cost	Gross profit	Final cost or profit*	
						Profit	Expense
No dwelling separation	Family recycle and secondary recycle			0	212.5–647.89	212.5–647.89	
	Transport fee to transfer station			5–10	0		5–10
	Transfer station			20–40	0		20–40
	Separation facility			80–110	12.96–31.1		48.9–97.04
	Transport fee after transfer station			10–20	0		10–20
Dwelling separation	Dwelling separation			80–150	243.6–660.85	93.6–510.85	
	Transport fee to transfer station			5–10	0		5–10
	Transfer station			20–40	0		20–40
	Transport fee after transfer station			10–20	0		10–20
Incineration	Grate furnace	Large-scale(above 300 t)		83–114	0		83–114
		Medium-scale (100–300 t)		104–140	0		104–140
		Small-scale (12.5–100 t)		130–167	0		130–167
		Residue	Mixed-MSW	10–20	0		10–20
			Separated-MSW	6–12	0		6–12
		Fly ash	Mixed-MSW	12–20	0		12–20
			Separated-MSW	9–15	0		9–15
	Fluidized bed	Large-scale (above 300 t)		67–98	0		67–98
		Medium-scale (100–300 t)		88–119	0		88–119
		Small-scale (12.5–100 t)		109–140	0		109–140
		Residue	Mixed-MSW	15–24	0		15–24
			Separated-MSW	10–18	0		10–18
		Fly ash	Mixed-MSW	25–60	0		25–60
			Separated-MSW	18–30	0		18–30
	Power generation	Small scale	Mixed-MSW	130–150	75–155	0–25	0–75
			Separated-MSW	120–140	95–175	0–55	0–55
		Medium scale	Mixed-MSW	100–120	75–155	0–55	0–45
			Separated-MSW	90–110	95–175	0–85	0–15
		Large scale	Mixed-MSW	70–90	75–155	0–85	0–15
			Separated-MSW	60–80	95–175	15–115	
	Energy recovery	Small scale	Mixed-MSW	85–100	50–90	0–15	0–50
			Separated-MSW	80–95	60–100	0–20	0–35
		Medium scale	Mixed-MSW	65–80	50–90	0–25	0–30
			Separated-MSW	60–75	60–100	0–40	0–15
		Large scale	Mixed-MSW	45–60	50–90	0–45	0–10
			Separated-MSW	40–55	60–100	5–60	
	Leachate treatment		Mixed-MSW	2.5–7.5	0		2.5–7.5
			Separated-MSW	1–5.5	0		1–5.5
Composting	Natural ventilation			29.2–43.2	0		29.2–43.2
	Reactor			46–47	0		46–67
	Aeration			38.2–41	0		38.2–41
	Compost product		Donation	2–4.4	0		2–4.4
			Landfill	8–17.6	0		8–17.6
	Residue		Incineration	22.4–36	0		22.4–36
			Landfill	11.2–24	0		11.2–24
	Leachate treatment			1–7.5	0		1–7.5
Landfill	Sanitary landfill	Without power generation		30–50	0		30–50
		Power generation (>200 t)		5–20	9–50	0–45	0–11
		Power generation (<200 t)		15–30	9–50	0–35	0–21
	Reactor landfill	Without power generation		45–65	0		45–65
		Power generation (>200 t)		5–30	15–75	0–60	0–15
		Power generation (<200 t)		20–40	15–75	0–55	0–25
	Semi-aerobic landfill			55–80	0		55–80
	Leachate treatment			1–7.5	0		1–7.5
	Leachate re-circulation			0.3–3.75	0		0.3–3.75

*The final cost/profit=cost–gross profit. Positive value means cost and negative one means profit.

Table 3 Recycle price and percentage of different compositions in MSW

Compositions	Recycle (%)	Weight (%)	Recycle price (RMB Yuan/kg)	Recycle value (RMB Yuan)
Plastic	20–40	3	2–6	12–72
Rubber	50–80	0.5	8–12	20–48
Paper	60–80	15	0.6–1.5	54–180
Cardboard	80–90	4	0.5–1.2	16–43.2
Textiles	60–70	2	0.2–0.4	2.4–5.6
Leather	60–70	0.5	1.0–1.5	3-5.-25
Other metal	50–60	1	10–20	50–120
Tin cans	95–100	1	8–12	57–120
Glass	70–90	8	0.2–0.4	11.2–28.8
Ferrous metal	90–95	2	1.0–2.0	18–38
Total				243.6–660.85

is simulated and the most economical processing way of municipal solid waste can be chosen using the model in this paper.

2.1 Assumed conditions

Every processing mode mentioned in this paper is a complete treatment way of municipal solid waste and can totally meet the qualification of innocent and recovery.

The cost of each processing method is the total cost to make the solid waste innocuous.

The innocent of MSW can be examined at the end of waste stream in each processing mode.

2.2 Mathematic model

Under the assumed conditions, the overall merit mathematic model of waste stream and economy of municipal solid waste disposal is constructed. The mathematic representation is shown as follows,

$$\min \sum_{j} y_{i,j} \quad x_{i,k} \geqslant 0 \tag{1}$$

where, i is the number of processing mode; j is the number of treatment cell; $y_{i,j}$ is the cost of number j treatment cell of number i processing mode; k is the matter number of number i processing mode; $x_{i,k}$ is the influence to environment of number k matter (matter is referred to any waste discharged to environment in every process, if any) of number i processing mode, when the matter is innocuous, and $x_{i,k} < 0$ when the matter is deleterious to the environment.

This model simulation was run by a program compiled with MatLab. The processing mode that costs the least can be achieved by the optimization calculation. Monte-Carlo method was used to randomly sample the data in the assigned area of the cost, to calculate the frequency of each simulation.

2.3 Boundary condition

The boundary conditions, that contain all the technologies summarized in Table 2, were determined as the mode of treatment/disposal techniques of municipal solid waste.

2.4 Initial condition

The initial conditions of the model are the spans of the treatment cost (Table 2), the mass percentage of matters and elements in every treatment cell (Tables 1 and 3). The initial conditions can change with situations and different results can be obtained.

2.5 Distribution function

The ranges of the treatment cost, mass percentage of matter and elements in every treatment cell under initial conditions were given by the maximum and minimum values. The data of initial conditions were simulated by standard normal function as shown by Eq.(2).

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{x^2}{2}) \tag{2}$$

In the standard normal function, the probability in the range of $x \in [-3, 3]$ was 99.74%, so there was nearly no value in the range of $x < -3$ and $x > 3$. If the parameter x accorded with standard normal distribution in a given span of $[a, b]$, the following equations were obtained:

$$\mu = \frac{a+b}{2}, \quad \sigma = \frac{b-a}{6} \tag{3}$$

Eq.(2) was modified to standard normal function in span of $[a, b]$:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right), \quad a \leqslant x \leqslant b \tag{4}$$

In the equation, a was the minimum of the value and b was the maximum one. The function could be implemented by command "normrnd (mu, sigma, m, n)" which could generate a $m \times n$ matrix in which the values coincide with standard normal distribution. Based on this normal function, the cost of treatment cells, mass percent of matter and elements were sampled in normal distribution.

2.6 Flowchart of numerical calculation

The program of numerical calculation was compiled according to Monte-Carlo Method. The flowchart is shown in Fig.2.

The loop part is the kernel of the program, which samples circularly to determine the cell cost and mass percent for every calculation step. When the loop time is satisfied, the loop stops and the results will be outputted. In this paper, 10000 times' loop is considered sufficient for stochastic calculation and it will take about 15 min to finish the loop calculation.

2.7 Modelling scenarios

Several typical scenarios are designed in this study. First of all, the "regular conditions" is defined as the conditions mentioned above, including the boundary conditions and initial conditions, which are absolutely agree with Tables 1, 2 and 3 except incineration is not considered when the amount of MSW production is below 12.5 t/d. Secondly, the lack of land will result in higher cost of landfills such as the landfill price for sanitary landfill, reactor landfill and semi-aerobic are going up to 90–150, 135–193, 75–95 RMB Yuan/t MSW. Thirdly, the situation of that MSW is separated at residential dwelling has been studied. Finally,

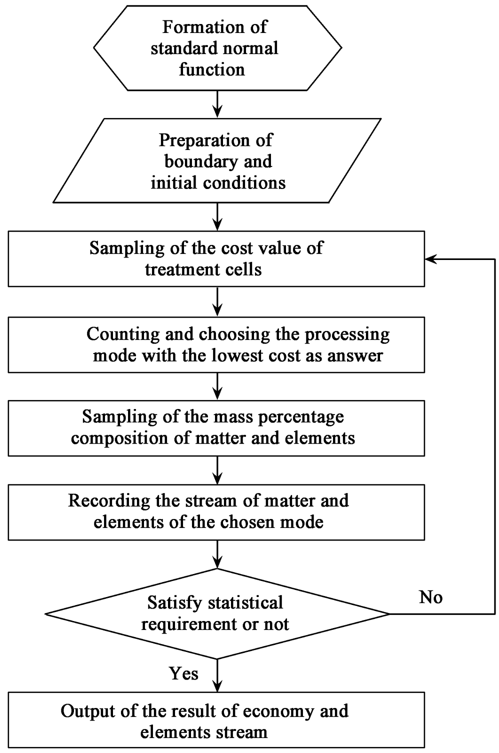

Fig. 2 Flowchart of numerical calculation.

the effects of city scale on the selected proportion of incineration as the optimal technology will be discussed in this paper.

3 Results and discussion

3.1 Simulation results under regular conditions

3.1.1 Proportion of treatment and disposal technologies under regular conditions

Table 4 shows the pickup times of treatment and disposal technologies under regular conditions, which simulated the current conditions of China.

As shown in the Table 4, the pickup frequency of landfill was over 99%. The pickup times of specific landfill technology were 2%, 61%, 1%, 36% times for sanitary landfill with leachate treatment and power generation, sanitary landfill with leachate re-circulation and power generation, reactor landfill with leachate treatment and power generation, reactor landfill with leachate re-circulation and power generation, respectively. The proportion of the above techniques is shown in Fig.3. Thus, when technical policies are established, landfill with power generation should be encouraged as the optimal method to treat and dispose MSW and leachate should be re-circulated.

Table 4 The pickup times of treatment/disposal technologies under regular conditions

Technology	Times
1-Incineration	0
2-Composting	16
3-Landfill without power	0
4-Landfill with power	9984
5-Facility separation	0

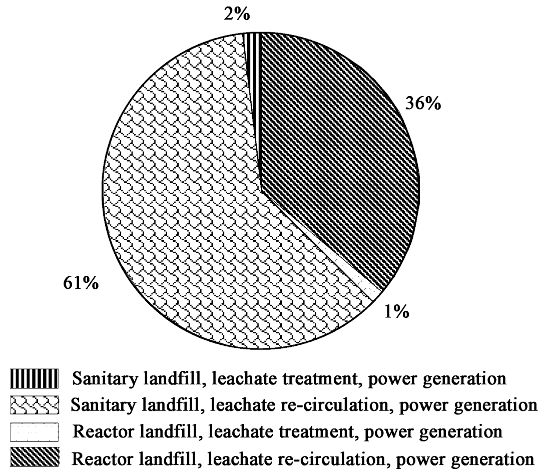

Fig. 3 Proportion of specific landfill under regular conditions.

3.1.2 C, H, O, N, S stream under the regular conditions

C, H, O, N, S stream was calculated when MSW was simulated to be treated by the optimal technology under the regular conditions. Table 5 indicated the final forms of the above five elements and their proportions in the corresponding elements of the initial MSW. As shown in the table, more than 58% of the five elements went to landfill.

3.2 Simulation results with high landfill cost

3.2.1 Proportion of the treatment/disposal technologies with high landfill price

Under the condition of high landfill cost, the model was calculated for another 10000 times. Fig.4 demonstrated the pickup frequency of the treatment and disposal technologies with high landfill price.

Results show that the pickup frequency of MSW separation at facilities was 70%. After the recyclable parts of MSW were recycled and reused, the MSW can be

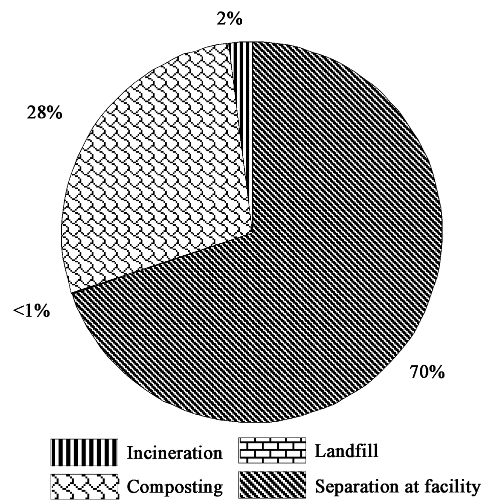

Fig. 4 Proportion of treatment/disposal technologies with high landfill price.

Table 5 C, H, O, N, S stream under the regular conditions

Final destination		Weight percentage (%)	Elemental weight percentage (%)				
			C	H	O	N	S
Recycled		24.2–29.7	18.9–23.1	19.0–23.3	19.9–24.3	7.5–9.2	10.7–13.0
Pre leachate re-circulation	Landfill	51.4–58.8	64.8–74.1	45.6–52.1	39.2–44.8	63.9–73.1	62.1–71.1
	Leachate	7.3–11.0	0.2–0.3	15.2–22.9	19.7–29.8	0.4–0.6	1.3–2.0
	Landfill gas	7.3–11.0	7.1–10.7	9.1–13.7	11.3–17.1	16.1–24.3	14.7–22.2
Post leachate re-circulation	Landfill	58.7–69.8	65.0–74.4	60.7–75.0	58.9–74.5	64.3–73.7	63.5–73.1
	Landfill gas	7.3–11.0	7.1–10.7	9.1–13.7	11.3–17.1	16.1–24.3	14.7–22.2

categorized into three types at separation facilities, which would be treated through incineration, composting and landfill. Such substances of high-quantity heat as paper, plastic will be treated through incineration. The substances which can be decomposed such as food waste would be treated through composting. Inorganic matters such as dirt and ashes would be treated though landfill.

Incineration, landfill and composting all have different equipment types. The model was run 10000 times each for incineration, landfill and composting systems to choose the optimal technology of each system.

(1) Incineration system: The pickup frequency of each technology as the optimal one in incineration system is shown in Fig.5.

As shown in the Fig.5, the pickup times of the grate furnace with power generation as the optimal technology was 54%, which should be firstly preferred. The secondly preferred technology was fluidized bed with power generation, which was 44% pickup times. Other techniques had a relatively lower frequency.

(2) Composting system: The pickup frequency of each technology as the optimal one in composting system is shown in Fig.6.

As shown in the Fig.6, the pickup times of the natural ventilation composting with compost donation and residue landfill as the optimal technology was 65%, which should be firstly preferred. The secondly preferred technology was natural ventilation composting with compost donation and residue incineration, which was 27% pickup times. Other technologies had a relatively lower frequency.

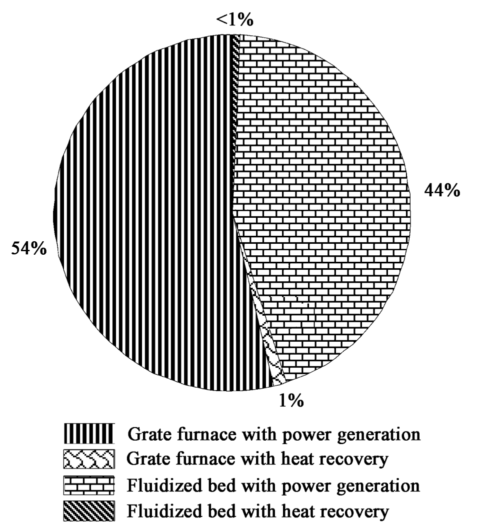

Fig. 5 Proportion of specific incineration technologies after facility separation.

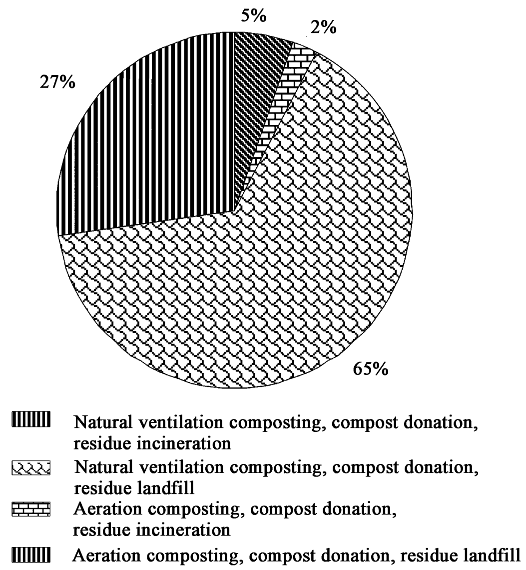

Fig. 6 Proportion of specific composting technologies after facility separation.

(3) Landfill system: Since it is the inorganic matters such as dirt and ash that enters the landfill system, the organic matters in MSW is low, which lead to the low landfill gas. So, reactor and semi-aerobic landfill are not suitable for treating MSW under this condition. Consequently, there are only two available technologies: that is, sanitary landfill with leachate recirculation and sanitary landfill with leachate treatment. The pickup frequencies of these two technologies are shown in Fig.7.

Fig.7 exhibited that the pickup frequency of sanitary landfill with leachate re-circulation amounted to 96%, which had far exceeded another one. So, leachate should be re-circulated instead of being treated directly.

3.2.2 C, H, O, N, S stream with high landfill price

C, H, O, N, S stream was calculated when the MSW was simulated to be treated by the optimal technology with high landfill price. 16.28%–21.37%, 16.63%–21.78%, 18.45%–23.74%, 7%–8.51% and 10.04%–12.71% of C, H, O, N, S were recycled and reused (Table 6). The remaining wood, plastic, rubber, leather, paper, cardboard, textiles of MSW were treated through incineration and the corresponding C, H, O, N, S were changed to incineration residues, gas and fly ash. Food and yard wastes were treated through composting and the corresponding C, H, O, N, S were altered to composting residues, gas and compost. The remaining glass, ferrous metals, other metals, dirt and

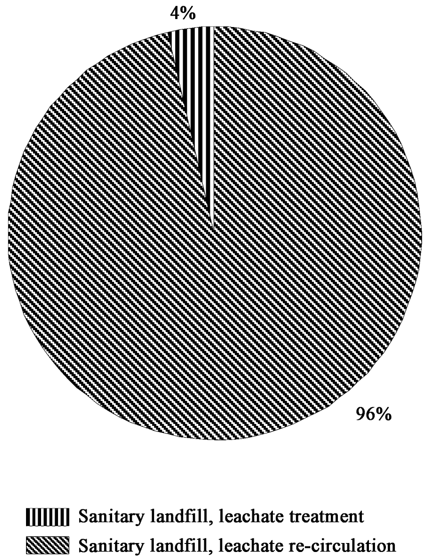

Fig. 7 Proportion of specific landfill technologies after facility separation.

ash were treated through landfill and the corresponding C, H, O, N, S were changed to landfill, leachate and gas. Incineration and composting residues were finally landfilled. Compost was land applied and become part of the soil. Fly ash was treated as hazard wastes. Table 6 indicated the final forms of the above five elements and their proportions in the corresponding elements of the initial MSW. As shown in the table, more than 40% of the five studied elements went to air.

3.3 Results with separation at residential dwelling

If MSW were separated at residential dwelling, the optimal technology and the C, H, O, N, S stream were the same as those after separation at facilities.

3.4 Effects of city scale on the selected proportion of incineration as the optimal technology

The selected proportion of incineration as the optimal technology varied with the differences in city scale as shown in Fig.8. This was because the construction and operation costs of grate furnace and fluidized bed were different at different scales in different cities. The treatment fee of MSW through small-scale incineration furnace is more expensive than that through large-scale incineration furnace. Therefore, in big cities and metropolitans where large amounts of MSW are produced and treated everyday, large-scale incineration furnace is suitable to be constructed. Whereas, in middle and small cities where the amount of MSW is relatively lower, it is comparatively wasting to build an incineration furnace for the cost to treat MSW through small-scale incineration furnace is very expensive. Accordingly, the pickup frequency of incineration as the optimal technology was low.

4 Conclusions

The pickup frequency of landfill is over 99% under regular conditions, which simulate the current conditions of China. When technological policies are established, landfill with power generation should be encouraged as the optimal method, in which, more than 58% of C, H, O, N, S went to landfill.

The pickup frequency of MSW separation at facilities is 70% with the assumption of high landfill price that simulate one of the possible future conditions of China. After the recyclable parts of MSW are recycled and reused, the MSW can be categorized into three types at separation facilities, which would be treated through incineration, composting and landfill. The pickup frequencies of the

Table 6 C, H, O, N, S stream with high landfill price (%)

Stream	C	H	O	N	S
Recycled	16.28–21.37	16.63–21.78	18.45–23.74	7.00–8.51	10.04–12.71
Landfill	2.2–3.63	0.42–1.51	1.07–5.5	5.08–6.5	2.2–3.63
Gas	57.38–66.73	58.61–67.87	41.88–60.7	67.7–87.54	51.43–61.32
Soil	13.25–15.90	13.30–15.96	20.03–33.39	4.36–20.91	19.78–27.69
Fly ash	0.01–0.06	0–0.07	0.18–0.58	0–0.01	1.89–5.16

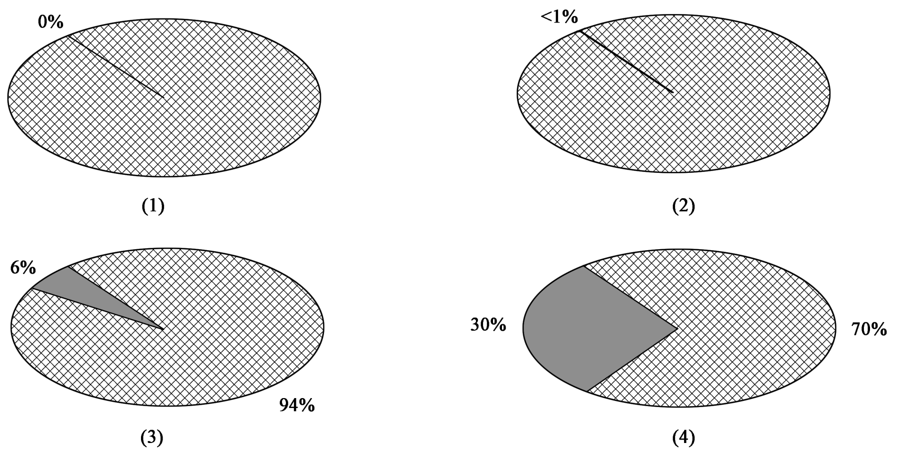

Fig. 8 Pickup proportion of treatment/disposal technologies with varied city scale. (1) small city; (2) middle city; (3) big city; (4) super big city.

grate furnace with power generation, natural ventilation composting with compost donation and residue landfill, sanitary landfill with leachate re-circulation as the optimal incineration, composting and landfill technologies were 54%, 65% and 96%, respectively. These three types of technologies should be preferred to treat MSW after facility separation. In this condition, more than 40% of the five studied elements went to air.

If MSW were separated at residential dwelling, the optimal technologies to treat MSW and element stream were the same as those after separation at facilities.

The selected frequency of incineration as the optimal technology was affected by the city scale. In big cities and metropolitans where large amounts of MSW are produced everyday, large-scale incineration furnace are suitable to be constructed. Whereas, in middle and small cities where the amount of MSW is relatively lower, it is comparatively wasting to treat MSW through incineration.

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