CHAPTER

2

Waste to energy in a circular economy approach for better sustainability: a comprehensive review and SWOT analysis

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2.1 Introduction

Waste production and management is a critical issue for all countries because it relates to environmental, social, and economic conditions. The rapid urbanization and industrialization in China have resulted in an increasing volume of municipal solid waste. The amount of municipal solid waste in China increased from 15,907 tons/day in 2007 to 17,537 tons/day in 2017 [National Bureau of Statistics of China (NBS), 2018; National Bureau of Statistics of China (NBS), 2008]. The municipal solid waste poses threats to environmental quality and human health, which is an obstacle to economic and social development. If not properly managed, the municipal solid waste would not only occupy huge land resources but also get in the way of city construction. To achieve

Waste-to-energy
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sustainable development, it is of utmost significance to promote the establishment of a waste-to-energy (WTE) system in a circular economy (CE) in China.

The concept of the CE has been proposed by China and the European Union as a solution that will allow countries, firms, and consumers to live in balance with the natural environment and close the loop of the product life cycle (Korhonen et al., 2018). In that context, the CE concept emerged in the 1970s, spreading into the domains of economy and business process management. The focus of the approach is on the minimization of pressure on natural and freshwater resources, as well as ecosystems, by means of various reuse and recycling schemes. A good example of implementing this approach is the waste management hierarchy (Pires and Martinho, 2019). The model can be summarized as "reuse–recycling–energy recovery–disposal" and has recently developed into the more complete set of priorities: "prevention–minimization–reuse–recycling–energy recovery–disposal." The concept of CE is rapidly capturing attention as a potential solution for the challenges of the current competitive scenario due to its ability to create synergies between environmental and economic development goals. CE seeks to replace the "take–make–consume–dispose" patterns with closed loops of material flows, made possible by combining a variety of different processes, such as maintenance, repair, reusing, refurbishing, remanufacturing, and recycling (Masi et al., 2017). A core assumption of the CE is therefore that the recovery of value from physical goods through the narrower cycles of reuse and refurbishment are superior both economically and environmentally to recycling and energy recovery. China was the first country in the world to adopt a law for the CE in 2008 (Korhonen et al., 2018).

WTE plays a crucial role in addressing various environmental issues such as climate change and the land use. It also ensures the security of energy supply, and becomes a key part of modern waste management and can reduce the dependence on fossil fuels (Pavlas et al., 2011; Psomopoulos et al., 2009; Wang et al., 2016b). WTE refers to the recovery of the energy from waste materials into usable heat, electricity, or fuel (Tan et al., 2015). The exploitation of fossil fuel has made many resource-based cities in China face the transition problem due to the resource depletion. These cities in China have made significant contributions to production activities and have promoted economic development of the national economy for decades. However, their sustainable development is challenging because of the depletion of natural resources and the inefficiency of energy utilization (Li and Dewan, 2017). As such, WTE provides an alternative solution to reduce the dependence on fossil fuels. Many studies have investigated various options of WTE in China, such as landfill (Han et al., 2016; Zhan et al., 2008), composting (Wei et al., 2000; Zhang et al., 2013), and incineration (Cheng et al., 2007; Zhao et al., 2016).

For example, landfill gas is an alternative source of energy which can be commercially exploited for power generation (Gendebien et al., 1992). Hoo et al. (2018) have studied landfill gas utilization through electricity generation in Malaysia. Smith and Aber (2018) investigated energy recovery through composting in New Hampshire. Zhao et al. (2016) made an analysis of the WTE incineration industry in China in terms of political, economic, social, and technological factors. However, few studies comprehensively have analyzed Chinese WTE situations, such as city-level waste utilization, waste components, and comparisons among three waste management options.

To fill this gap, we first investigated Chinese waste by providing a comprehensive analysis of the current status of waste generation and WTE systems. A review of the types of waste generation and waste management options is then presented. Next, an analysis of strengths, weaknesses, opportunities, and threats (SWOT) of WTE in China is discussed. Some policy implications are proposed to promote the establishment of the WTE system.

2.2 Method and data

2.2.1 Method

In this study, SWOT analysis is adopted to analyze the development of WTE systems. SWOT is a useful tool for audit and analysis of the overall strategic position of the business and its environment by identifying the strengths, weakness, opportunities, and threats of project development (Pesonen and Horn, 2014). Strengths indicate characteristics of a project which give it an advantage over others. Weaknesses mean qualities of the project which hinder it from achieving its full potential. Opportunities suggest elements in the environment that the project could exploit to its advantage. Threats refer to elements in the environment which could cause trouble for the project. Strengths and weaknesses are the internal factors of project development, while opportunities and threats are the external factors. SWOT analysis is valuable for the evaluation of management procedures in companies, projects, and plans (Samolada and Zabaniotou, 2014). Although SWOT analysis is applied initially to economic research, it has been extended to a variety of research fields and is increasingly being adopted in environmental analysis. For example, Samolada and Zabaniotou (2014) used a SWOT analysis for the comparison of two different applications of refuse-derived fuel. Antonopoulos et al. (2011) adopted SWOT analysis to evaluate applications of new WTE technologies. In this study, we use SWOT analysis to study the WTE system in China.

2.2.2 Data

The data of waste, including special waste, overall construction waste, industrial waste, commercial waste, and domestic waste, are collected from China statistical yearbooks from 2007 to 2017. The number of waste treatment plants, treatment capacity, and volume of wastes disposed of in landfills, incineration, and composting are collected from China statistical yearbooks from 2007 to 2017. Consumption wastes collected and transported and treatment rate of consumption on wastes data are sourced from China statistical yearbooks from 2007 to 2017. The ratio of industrial solid wastes being comprehensively utilized is derived from China City Statistical Yearbook in 2018.

2.3 Results analysis

2.3.1 The framework of waste to energy in a circular economy

The traditional economic chain is a one-way flow, which can be expressed as "virgin materials and energy from the environment to production activities and residential consumption to pollutants." The traditional economy is characterized by high energy consumption, high emissions, and low level of resource utilization. By contrast, in a CE, the flow of material and energy can be as expressed in Fig. 2.1. Fig. 2.1 depicts the framework of material and energy flow between the WTE system and the environment in a CE. The framework shows how to realize the CE. The advantage of a CE is the circular flow of material and energy that is characterized by low energy consumption, low emissions, and high level of resource utilization. In the traditional economy, human beings exploit natural resources from the environment to produce goods to meet the needs of human production and living activities. During the production process, waste or pollutants will be ceaselessly discharged into the air, water, soil, and ecosystem. However, in a CE, the reusable waste can be recycled or transformed into energy, such as green fuel pellets, biogas, biochar, refuse-derived fuel, heat, and electricity. This circular form can mitigate the impacts of the production activities on the environment to the minimum extent, making the production activities more environmentally friendly and economically feasible.

There are two sources of municipal solid waste generation, that is, residential consumption (e.g., cooking) and production activities (e.g., farming, coal mining, and manufacturing), as shown in Fig. 2.1. Domestic waste is generated from residential consumption. Garbage classification can not only improve the efficiency of waste disposal but can also achieve recycling of reusable resources. For example, recyclable waste can be used to make

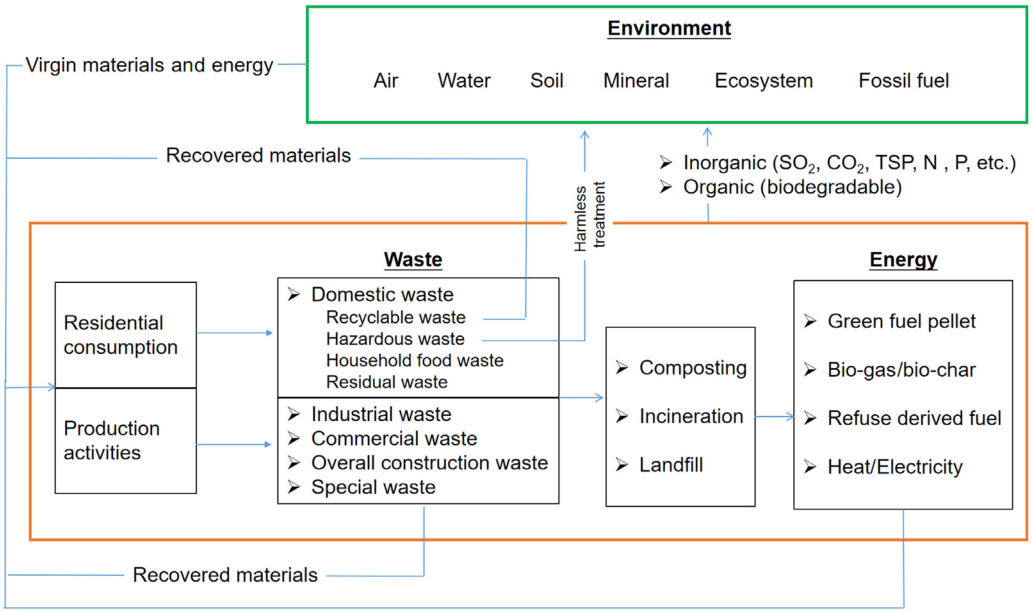

FIGURE 2.1 Framework of material and energy flow between WTE systems and the environment in a circular economy. *WTE*, Waste-to-energy.

paper, and the technological process of making paper is fragmentation, pulp-making, screening, washing, bleach, and papermaking. Recycled plastic is another common practice of recycling. The technological process of plastic recycling includes separate collection, sorting, cleaning, fragmentation, and recycling. Hazardous waste can be returned to the environment after it is properly treated. Household food waste can be treated by composting. The amount of household food waste may have experienced an increasing trend because of the implementation of garbage classification in China since 2019. As for residual waste, it can be treated by incineration to generate electricity or supply heat because of its high heat value.

In 2019 garbage classification was implemented in 46 key cities in China, such as Shanghai, Beijing, Tianjin, Changchun, and Guangzhou. These 46 cities in the pilot program can accelerate the construction of an integrated garbage treatment system with dumping, collecting, transportation, disposal, and recycling process. In general, the classified waste can be treated more properly and effectively and reduce the load of sewage treatment. Garbage classification can be generally divided into four categories, namely recyclable waste, household food waste, residual waste, and other waste (China Daily, 2019). Take Shanghai for example, the amount of household food waste saw a significant increase to 8200 tons in July 2019 from only 3500 tons in July 2017. By contrast, the amount of residual waste witnessed a dramatic decline, dropping by around 21% compared with the level of July 2018 (Chinanews, 2019).

Industrial waste, commercial waste, overall construction waste, and special waste are generated from production activities (Fig. 2.1). These wastes can be recycled to generate materials or are treated through landfill, incineration, and composting to produce energy. Commercial waste represents about 30.01% in municipal solid waste in 2017, while industrial waste takes up a mere 10.34% (Fig. 2.4).

2.3.2 Status of China's waste management

At the national level, according to Fig. 2.2, the volume of waste collected and transported was 152.145 million tons in 2007, while the figure had increased by 41.45% after 10 years. With the rapid growth in the amount of waste generation, the treatment rate of consumption on wastes increased steadily, rising from 62.0% in 2007 to 97.7% in 2017 (Fig. 2.2). This shows a positive trend for waste treatment over the last decade in China and provides a solid foundation for WTE systems.

At the city level, based on Fig. 2.3, there are three cities whose industrial solid wastes comprehensively utilized ratio reached 100% in 2017, namely Dayong, Haifeng, and Zaozhuang (Fig. 2.3). There are 55 cities, such as Changzhou, Tianjin, and Wenzhou, whose industrial solid

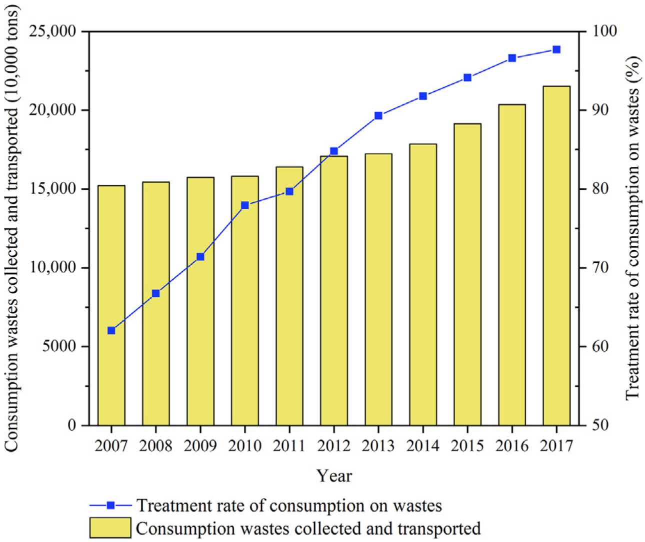

FIGURE 2.2 The amount of collected and transported wastes, and the treatment rate of wastes from 2007 to 2017.

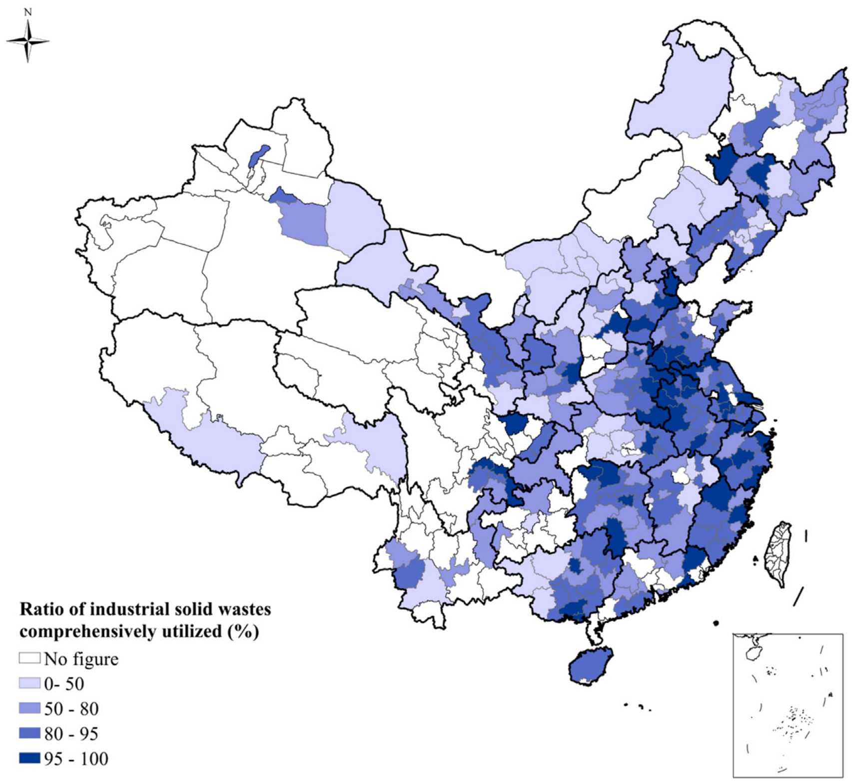

FIGURE 2.3 The ratio of industrial solid wastes comprehensively utilized in 257 cities in China in 2017.

wastes comprehensively utilized ratio was over 95% in 2017, while 104 cities utilized more than 90% of industrial solid wastes (Fig. 2.3). Forty-six cities, such as Taiyuan, Jixi, and Jilin, only utilized less than 50% of industrial solid wastes in 2017 (Fig. 2.3). As such, there are still great disparities in terms of the utilization of industrial solid waste among cities. The ratio of industrial solid wastes comprehensively utilized in the Eastern region is higher than in other regions. Policies for removing the technology diffusion barriers among cities or regions should be issued to accelerate the cooperation between different regions and technology diffusion about municipal solid waste management. The spillover of knowledge and technology allows a city or region to take advantage of resources to promote WTE development in a CE effectively and rapidly.

Fig. 2.4 shows the average solid waste quantities by type per day in China from 2007 to 2017. Municipal solid waste includes domestic waste, commercial waste, and industrial waste. Domestic waste is the main contributor to municipal solid waste, accounting for around 59.65% in 2017. Commercial waste represents about 30.01% of municipal solid waste in 2017, while industrial waste accounts for 10.34% of municipal solid waste. From the perspective of time series, the amount of domestic waste experienced a small increase from 6370 tons/day in 2007 to only 6400 tons/day in 2017, an increase of a mere 0.47% during 2007–17. However, commercial waste and industrial waste saw a significant increase in quantities, rising by 47.03% and 79.03%, respectively.

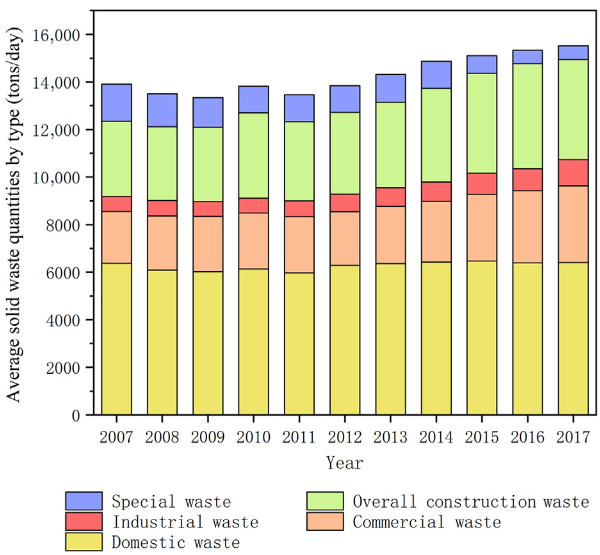

FIGURE 2.4 Average solid waste quantities by type per day in China, 2007–17.

Construction waste covers waste arising from construction and demolition activities but excludes material delivered to public filling areas for land reclamation and formation. Special waste includes animal carcasses, abattoir waste, condemned goods, waterworks and sewage treatment sludge, sewage works screening, livestock waste, clinical waste, and chemical waste delivered to landfills. Special waste is the only waste type that witnessed a decline over the study period, decreasing from 1560 tons/day in 2007 to 580 tons/day in 2017.

2.3.3 Reviews and challenges of municipal solid waste management

Table 2.1 shows the waste types and major waste management options in China. There are many kinds of waste that have been studied in China, such as garden waste biomass, coal mining waste, carcass, kitchen waste, domestic waste, swine manure, food waste, and industrial waste. There are three main options to deal with the waste, namely landfill, composting, and incineration.

Table 2.2 demonstrates the SWOT of the WTE industry in China. According to the strengths and opportunities shown in Table 2.2, China has great potential to accelerate the establishment of a WTE system in a CE and further promote its sustainable development. WTE is a feasible and rewarding choice in the long run. There are many strengths to promote WTE development. WTE is an environmentally sustainable solution for municipal solid waste. It can not only reduce the amount of waste but turn waste into energy for production and consumption activities. By doing so, the company/government can earn additional income. As for opportunities, more energy can be attained from waste, which helps to reduce the exploitation and use of fossil fuel. According to the Chinese Government (2011), there are 69 resource-dependent cities in China which are facing resource exhaustion problems. Resource-exhausted cities rely heavily on resource-related industries, such as the heavy manufacturing industry and coal mining industry. However, overexploitation accelerates the rate of depletion of fossil fuel in China. Therefore WTE can solve resource depletion to some extent and provides a feasible solution for the transition of the city's development. At the same time, the development of the WTE industry requires the research and development of relevant technologies which could attract more investment and create new jobs for society. In recent years, the Chinese Government has shed light on garbage classification to promote the development of WTE systems. However, waste treatment in China is still in the development stage, and attention should be paid to some technical strengthening and management details. Pretreatment technology is a significant part of WTE management.

TABLE 2.1 The literature of waste types and major waste management options in China.

No.	Research topic	Reference	Main content	Scale
		Waste by type		
1	Garden waste biomass	Shi et al. (2013)	Literature and experimental analysis of garden waste biomass	China
2	Coal mining waste	Haibin and Zhenling (2010)	Discusses and analyzes the mining waste management in Jincheng Anthracite Mining Group, Shanxi province	Shanxi province in China
3	Carcass	Wang et al. (2016a)	Explores the carcass composting by establishing different composting systems	Guangzhou city, China
4	Kitchen waste	Li et al. (2016)	Investigates the current situation of kitchen waste treatment methods in China and other countries	China
5	Domestic waste	Han et al. (2015)	Analyzes the characteristics of domestic waste, the influence factors of characteristics, and resident's willingness of participation in domestic waste management	The rural area of Southwest China
6	Swine manure	Wu et al. (2011)	Investigates the behavior and degradation kinetics of three tetracyclines and their degradation products in a pilot scale swine manure composting	China
7	Food waste	Guo et al. (2018)	Proposes a mode of source classification of residents—composting in situ and designed a set of complete equipment for food waste composting	China
8	Food waste	Uçkun Kiran et al. (2014)	Examines the state-of-the-art of food waste fermentation technologies for renewable energy generation	Asia-Pacific countries
9	Industrial waste	Tsai (2010)	Gives the current status of industrial waste generation and its management about governmental regulations and policies	Taiwan

(*Continued*)

TABLE 2.1 (Continued)

No.	Research topic	Reference	Main content	Scale
Waste management options				
1	Landfill	Han et al. (2016)	Investigates 96 groundwater pollutants, 2 visual and 7 aggregate pollutants and analyzes their link with landfill	China
2	Landfill	Zhan et al. (2008)	Field and laboratory testing methods	Suzhou city, China
3	Composting	Zhang et al. (2013)	Compares the emissions of volatile sulfur compounds and the discharge of leachate during composting	Beijing, China
4	Composting	Wei et al. (2000)	Introduces the current situation of municipal solid waste and sewage sludge production in China and reviews the composting and compost applications in China	China
5	Incineration	Zhao et al. (2016)	Analyzes the factors that influence the WTE industry and introduces some WTE plants in China	China
6	Incineration	Cheng et al. (2007)	Introduces a novel WTE incineration technology based on cofiring of municipal solid waste with coal in a grate-circulating fluidized bed incinerator	Changchun city, China
7	Landfill, composting, and incineration	Cheng and Hu (2010)	Provides an overview of the WTE industry and discusses the major challenges in expanding WTE incineration in China	China

WTE, Waste-to-energy.

Pretreatment technology refers to the technology that is carried out before the posttreatment of solid waste. Garbage classification is the most important content of pretreatment technology. The newly launched garbage classification in 2019 provides opportunities to overcome some weaknesses and threats. Even though 46 key cities in China have been listed in the pilot program of garbage classification in 2019, the classification and placement of solid waste are still far less than enough. Policymakers should

TABLE 2.2 Strengths, weaknesses, opportunities, and threats analysis of waste-to-energy (WTE) in China.

Internal factors	
Strengths	**Weaknesses**
1. A environmentally sustainable solution for municipal solid waste treatment **2.** Reduction of the amount of municipal solid waste by landfilling **3.** An alternative solution of turning waste into energy for production and consumption activities, such as green fuel pellet, biogas, biochar, refuse-derived fuel, heat, and electricity **4.** Additional avenue through WTE systems **5.** Waste being treated in a sustainable manner	**1.** Technological immaturity of WTE systems **2.** Logistic cost and complexity of supply chain management **3.** The low heat value of municipal solid waste in China because of the insufficient garbage classification **4.** Great disparities among Chinese cities in wastes comprehensively utilized because of different economic development level and technology barriers
External factors	
Opportunities	**Threats**
1. Reduce the exploitation and use of fossil fuel **2.** The development of the WTE industry attracts investment and creates new jobs **3.** The demand for promoting garbage classification and improve garbage classification standards and supervision **4.** Nowadays nearly 5000 vehicles for transporting kitchen garbage were allocated in the 46 cities and about 1000 vehicles for hazardous waste in 2019. The full implementation of garbage classification in all of the cities in China in the future ensures the feedstock of WTE systems	**1.** Public acceptance is required and there is some misunderstanding and even resistance to some options, such as incineration. The public is unwilling to have waste management facilities around their residential area **2.** The possibilities of technological backwardness, lack of supervision, and opaque information during the operation of plants **3.** Lack of national strategy or incentives for the development of new WTE technologies **4.** Relatively poor pretreatment management, such as insufficient garbage classification awareness and habit

WTE, Waste-to-energy.

increase the public's awareness of garbage classification. The success of this program has a great impact on the perfecting of the WTE system.

Table 2.3 shows the municipal solid waste disposal in terms of landfill, incineration, and composting in China from 2007 to 2019. The number of plants used for landfills is significantly larger than that of incineration and composting, increasing from 366 to 654 units from 2007 to 2017. As for treatment capacity, the landfill can manage the largest amount of

TABLE 2.3 The status of municipal solid waste disposal in China from 2007 to 2019.

Year	Number of plants for wastes treatment			Treatment capacity (ton/day)			The volume of wastes disposed (10,000 tons)		
	Landfill	Incineration	Composting	Landfill	Incineration	Composting	Landfill	Incineration	Composting
2007	366	17	66	215,179	7890	44,682	7632.7	250.0	1435.1
2008	407	14	74	253,268	5386	51,606	8424.01	174.01	1569.74
2009	447	16	93	273,498	6979	71,253	8898.61	178.83	2021.96
2010	498	11	104	289,957	5480	84,940	9598.3	180.8	2316.7
2011	547	109	21	300,195	94,114	14,810	10,063.7	2599.3	426.6
2012	540	138	23	310,927	122,649	12,692	10,512.5	3584.1	393.0
2013	580	166	19	322,782	158,488	11,030	10,492.7	4633.7	267.6
2014	604	188	26	335,316	185,957	12,182	10,744.3	5329.9	319.6
2015	640	220	30	344,135	219,080	13,679	11,483.1	6175.5	354.4
2016	657	249	34	350,103	255,850	15,398	11,866.4	7378.4	428.9
2017	654	286	73	360,524	298,062	21,303	12,037.6	8463.3	533.2

waste, at 360,524 ton/day, followed by incineration (298,062 ton/day) and composting (21,303 ton/day). The amount of municipal solid waste treated through landfill is around 120.376 million tons (57.3%) in 2017, rising from 76.327 million tons (80.9%) in 2007. This suggests that landfill is traditional as well as the dominant method for wastes treatment in China over the last decade (Table 2.3). However, landfilling was always the least desirable management technology from the perspective of cost and GHG emissions (Minoglou and Komilis, 2013).

Owing to rising landfill costs, severe scarcity of landfill sites, and increased environmental awareness, incineration is an alternative disposal method to solve these problems. WTE incineration is attracting growing attention due to the promotion of renewable energy developments and pressure on efficient land use. Noticeably, the volume of wastes disposed of by incineration has experienced a rapid increase, rising from 2.5 million tons in 2007 to 84,633 million tons in 2017. From 2007 to 2017, WTE not only dealt with the rapidly growing amount of municipal solid waste, arguably due to the expansion of the population, but also could satisfy the demand for energy by means of heat and electricity (de Souza et al., 2014; Pavlas et al., 2011). However, there are some barriers that hinder the construction of incineration plants. The most critical one is public acceptance, and there are some misunderstandings and even resistance to incineration (Huang et al., 2015). Some people argue that the air or water nearby may be polluted by some pollutants generated in the WTE incineration process, such as dioxins and heavy metals (Psomopoulos et al., 2009). Nowadays, more and more people have a strong awareness of environment protection and require a safer and better living environment. Although there are sufficient emission standards and advanced technologies to ensure the operation of the incineration plants, the public questions whether there are possibilities of technological backwardness, lack of supervision, and opaque information during the operation of plants. The other barrier is that the heat value of municipal solid waste is generally low in China. The main reason is that garbage classification is rarely done. The public does not have strong awareness or the habit of garbage classification.

The volume of wastes treated by composting has experienced a significant decrease since 2010, dropping from 23,167 million tons in 2010 to a mere 2676 million tons in 2013. Composting is mainly applied for treating organic waste, about 2.5% of the total amount of municipal solid waste being disposed of in 2017 (Table 2.3). Organic waste needs to be first classified from municipal solid waste. Therefore garbage classification should be carried out to smooth away the difficulties of this step. Household food waste refers to organic waste, which is easy to rot and decompose. It can be used to make compost, which is a kind of organic fertilizer. A variety of plant residues, such as straw, peat, leaves, and weeds, are used as the primary raw material. Organic fertilizer is composted through the mix of waste of people and animals.

2.4 Discussion

Current studies about WTE in China have been limited in literature and theoretical or case analysis, and the efficiency of WTE systems are still unknown. Chinese government should use the minimum inputs, such as capital and labor, to produce the maximum outputs, namely energy. Therefore a comprehensive evaluation of the efficiency of different options about how to turn waste into energy should be carried out. More specific measures can be put forward to improve the efficiency cost-effectively. In future work, the flowing method can be used to figure out the efficiency of WTE systems of a decision-making unit. Nonradial directional distance function, a type of data envelopment analysis, is a useful method to evaluate the total factor environmental performance and has been adopted to determine the efficiency of resource utilization by many scholars (Barros et al., 2012; Bian et al., 2013; Sueyoshi and Goto, 2012; Wang et al., 2013).

Assume that K, L, and W are capital stock, labor force, and waste, respectively. These represent inputs of the production process. Y, E, and C mean GDP (good output), waste (good output), and CO_2 emissions (bad output), respectively. The joint production technology (T) can be obtained as

$$T = \{(K,\ L,\ W,\ Y,\ E,\ C) : (K,\ L,\ W) \text{ can produce } (Y,\ E,\ C)\} \tag{2.1}$$

The nonradial directional distance function is not only capable of decreasing inputs/bad outputs and increasing good outputs simultaneously but also can adjust the inputs and outputs at different rates (Zhou et al., 2012). In this regard, nonradial directional distance function has been widely adopted to evaluate total factor environmental performance because of better discriminating power and improved efficiency measurement. We denote the value of nonradial directional distance function as $\vec{ND}(K, L, W, Y, E, C; g)$. Then the nonradial directional distance function can be expressed as (Zhou et al., 2012):

$$\overrightarrow{ND}\,(K, L, E, Y, C; g) = \sup\{w^T\beta : (K, L, E, Y, C + g \times \mathrm{diag}(\beta)) \in T\} \tag{2.2}$$

We obtain the value for $\vec{\mathrm{ND}}(K, L, E, Y, C; g)$ by solving the following DEA-type model. Data envelopment analysis (DEA) provides a methodology within a set of comparable decision-making units to identify the units with the best performance by forming an efficient frontier.

$$\overrightarrow{\mathrm{ND}}\,(K, L, E, Y, C; g) = \sup\left\{w^T\beta : \left(K, L, E, Y, C + g \times \mathrm{diag}(\beta)\right) \in T\right\},$$

$$s.t. \sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t K_n^t \leq (1-\beta_K)K_{n'}$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t L_n^t \leq (1-\beta_L)L_{n'}$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t W_n^t \leq (1-\beta_W)W_{n'}$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t Y_n^t \geq (1+\beta_Y)Y_{n'},$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t E_n^t \geq (1+\beta_E)E_{n'}$$

$$\sum_{t=1}^{T}\sum_{n=1}^{N} z_n^t C_n^t = (1-\beta_C)C_{n'}$$

$$z_n^t \geq 0, \sum z_n^t = 1, \beta_Y, \beta_E \geq 0, 0 \leq \beta_K, \beta_L, \beta_W, \beta_C \leq 1, t = 1, 2, \ldots T, n = 1, 2, \ldots N. \tag{2.3}$$

where $\sum z_{ni}^t = 1$ denotes variable returns to scale.

The indicator that used to evaluate WTE efficiency is the total factor WTE performance index (TWTEPI). TWTEPI can be expressed as follows:

$$\mathrm{TWTEPI} = \frac{(E - \beta_E^* E)/(W + \beta_W^* W)}{E/W} = \frac{1 - \beta_E^*}{1 + \beta_W^*} \tag{2.4}$$

TWTEPI lies between zero and unity. If TWTEPI gets higher, it means that the performance of the WTE system gets better. If TWTEPI is equal to unity, it suggests that the WTE system is located on the frontier.

Based on the obtained TWTEPI, the improvement space of each factor can be known. For example, how much can a decision-making unit cut down inputs (capital, labor, and waste)/bad outputs (CO_2 emissions). How much can a decision-making unit increase the good outputs, namely energy and gross domestic products. Some targeted policy

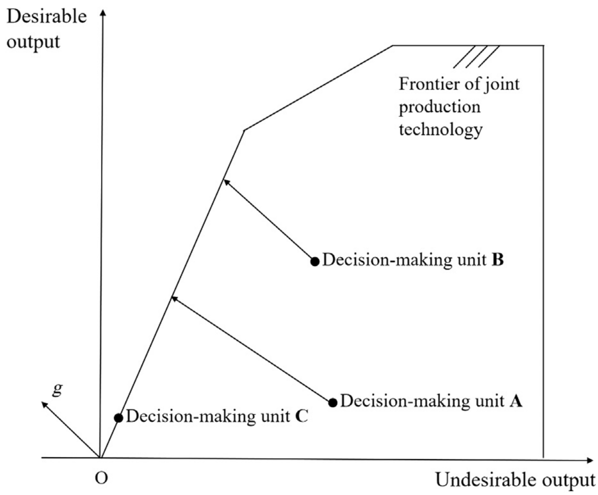

FIGURE 2.5 A graphical illustration of the improvement of total factor WTE performance. *WTE*, Waste-to-energy.

implications can be put forward to adjust inputs and outputs of the production process to improve the performance of the WTE system.

Fig. 2.5 illustrates the change of total factor WTE performance. For decision-making unit A, it produces a lot of undesirable output, such as CO_2 emissions, and low levels of desirable outputs, such as gross domestic product and energy. Therefore decision-making unit A is inefficient in terms of WTE performance. However, based on the same amount of inputs, decision-making unit B can produce less undesirable output and more desirable outputs. As such, we can conclude that decision-making unit B is more efficient than A in the WTE system. Both decision-making unit A and B have improvement space by reducing undesirable outputs and increasing desirable outputs. Decision-making unit C is located on the frontier of joint production technology, indicating that decision-making unit C has the best efficiency in WTE.

2.5 Conclusion

WTE contributes significantly to a CE by generating energy and promoting sustainability. This chapter first investigated Chinese waste by providing a comprehensive analysis of the current status of waste and WTE management. Literature reviews of waste by types and management options were then presented. The SWOT of WTE in China were analyzed and discussed. The main findings and policy implications are as follows:

First, along with urbanization, population growth, and industrialization, the volume of Chinese waste increased from 152,145 million tons in 2007 to 215,210 million tons in 2017. With the rapid growth in the waste amount, the treatment rate of consumption on wastes increased steadily, rising from 62.0% in 2007 to 97.7% in 2017. The landfill is the traditional and the dominant option of waste management, at 120.37 million tons in 2017, followed by incineration (84.63 million tons) and composting (5.33 million tons). This shows a positive trend of waste treatment over the last decade in China and provides opportunities for the WTE system.

Second, there are three cities whose industrial solid wastes comprehensively utilized ratio reached 100% in 2017, namely Dayong, Haifeng, and Zaozhuang. One hundred and four cities could utilize more than 90% of industrial solid wastes (Fig. 2.3). However, 46 cities, such as Taiyuan, Jixi, and Jilin, only utilized less than 50% of industrial solid wastes in 2017. As such, there are still great disparities in terms of the utilization of industrial solid waste among cities. The ratio of industrial solid wastes comprehensively utilized in the eastern region was highest. An approach for removing the technology diffusion barriers among cities or regions should be carried out to accelerate the process of management experience. The spillover of knowledge and technology allows a city or region to take advantage of resources to promote WTE development in a CE effectively and rapidly.

Third, China has great potential to accelerate the establishment of a WTE system and the newly launched garbage classification in 2019 provides opportunities to overcome some weaknesses and threats. Waste treatment of China is still in the development stage, and we need to pay attention to some technical strengthening and management details. Pretreatment technology is a significant part of WTE management. Garbage classification is the most important content of pretreatment technology. Even though 46 key cities in China have been listed in the pilot program of garbage classification in 2019, classification and placement of solid waste are still far less than sufficient. Policymakers should increase the public's awareness of garbage classification. The success of this program has a great impact on the perfecting of the WTE system.

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