Circular Economy 2 (2023) 100041

Contents lists available at ScienceDirect

Circular Economy

journal homepage: www.journals.elsevier.com/circular-economy

Original Research

Generation and management of municipal solid waste in top metropolitans of China: A comparison with Singapore

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A R T I C L E I N F O

Article history:
Received 3 February 2023
Received in revised form
30 April 2023
Accepted 9 May 2023
Available online 13 May 2023

Keywords:
Municipal solid waste (MSW)
Metropolitan
Waste management
China
Singapore

A B S T R A C T

With the rapid urbanization in the last decades, especially after the year 2000, several metropolitans were formed. e.g., Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, and Chongqing that locate at four world-class megalopolises across China. The generation and management of municipal solid waste (MSW) are important components for city development, both of which are spatiotemporally heterogeneous among these metropolitans, as a result of diverse socioeconomic statuses. This study attempts to sufficiently reveal the spatiotemporal heterogeneity by determining the MSW per capita, MSW composition, and proportion of each management strategy (landfilling, incineration, and compositing). Singapore is taken for comparison, for it is a Chinese community and well-known for its outstanding performance in environmental sanitation. Results show that MSW per capita is highly dependent on GDP per capita, and exerts an increasing tendency with time, but can be relieved with MSW reduction policy. For each metropolitan, the development of landfilling and incineration fits the Kuznets curve well, and government policy is a more determinant factor than GDP. MSW composition is also time- and location-dependent, and source sorting generally favors the subsequent resource utilization including the mainstream incineration. In addition to MSW generation and management, the action, goal, and experience in Singapore are expatiated, which are believed to be of referential significance for these metropolitans.

1. Introduction

As the largest developing country worldwide, China has experienced rapid population growth and urbanization in the last decades. The population increases by over 1.0×10^8 every decade, reaching 14.1×10^8 in 2020 (Fig. 1(A)). The urbanization rate reached 63.9% in 2020 (Fig. 1(A)), which means that over 9.0×10^8 people currently live in the city pursuing a better life. The rapid urbanization gives birth to four world-class megalopolises, namely, the Beijing-Tianjin-Hebei Region, Changjiang Delta Region, Zhujiang Delta Region, and Chengdu-Chongqing Economic Circle, all of which contribute significantly to China's development from economics to politics, culture, and society (Liao et al., 2019; Liu et al., 2018; Zheng et al., 2016). These megalopolises are heterogeneously located in different regions of China, and contain several metropolitan, e.g., Beijing (BJ), Shanghai (SH), Guangzhou (GZ), Shenzhen (SZ), Tianjin (TJ), and Chongqing (CQ).

One of the inevitable issues for city development is municipal solid waste (MSW) management, which is highly dependent on the mass (Fig. 1(C)) and composition. The MSW mass per capita (MSW_{mp}) is of interest because it is a core indicator of the environmental pressure induced by MSW generation, and contributes to better MSW management planning. MSW_{mp} in developed countries is mainly distributed within 0.52−0.76 t/a, but 0.11−0.53 t/a in developing countries (Karak et al., 2012). China's GDP grew and tended to accelerate after 2000 (Fig. 1(B)), and steadily ranks second worldwide since 2010. The GDP per capita is ~200 USD in 1980, and increased by ~500 times to ~11,000 USD in 2020. There are other factors influencing the MSW_{mp}, e.g., geographical location, habits and customs, and resident average

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https://doi.org/10.1016/j.cec.2023.100041

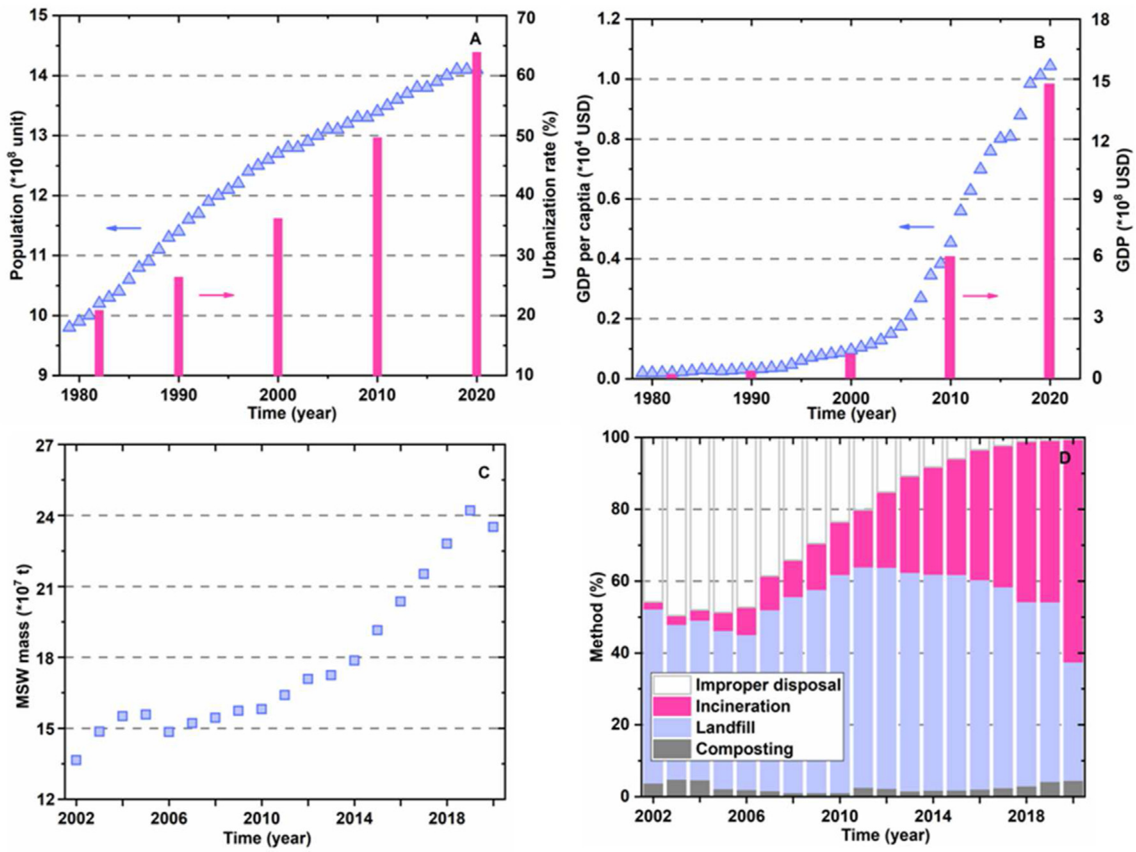

Fig. 1. (A) Population and urbanization rate; (B) GDP and GDP per captia in China from 1980 to 2020; (C) MSW mass; and (D) proportions of incineration, landfilling, composting, and improper disposal for MSW in China from 2002 to 2020. All data are collected from the latest National Bureau of Statistic of China (NBSC, 2021).

age. It has been previously reported that the MSW_{mp} discrepancy in two countries with almost equal GDP per capita can reach 0.4 t (Eurostat, 2021). The variability of MSW_{mp} in typical Chinese cities has been reported (Han et al., 2016; Xiao et al., 2020), but not properly correlated with socioeconomic factors.

Sanitary management of the generated MSW is crucial for modern city development. On a national scale, 99.8% of MSW was sanitarily disposed of in 2020, which is significantly higher than 54.2% in 2002. Landfilling and incineration are two main strategies that contribute to sanitary management, but their development trends are different (Chen et al., 2010). The landfilling proportion shrinked after 2012 and reached 33.2% in 2020, whereas incineration developed rapidly and its proportion was 62.0% in 2020 (Fig. 1(D)). Likewise, the sanitary management and strategy evolution should be variable among different cities as a result of varied socioeconomic factors, but has not been extensively explored.

In addition to the rapid development of incineration, another mainstream direction for MSW management is source sorting. The promulgations of China's Work Plan on Zero-waste City Pilot Program and revised law of Environmental Pollution Prevention Caused by Solid Waste call for source sorting. In 2021, the 14th Five-Year Plan on MSW Sorting and Treatment Facility was launched to promote national source sorting (Shenzhen Circular Economy Information Platform, 2020). The average MSW recovery rate in 46 major cities was only 30.4% by 2020 (National Development and Reform Commission of China, 2020), as a result of lacking source sorting. In comparison, Singapore is well-known for its outstanding performance in environmental sanitation. Recently, Singapore government promulgates the Zero Waste Masterplan to achieve 70% recycling rate by 2030 (MEWR, 2023). Experience and action from Singapore are perhaps of referential significance for China.

Using the above mentioned six metropolitans as the research areas, the first work of this study is to explore the spatiotemporal heterogeneities of MSW generation and management by considering various socioeconomic factors. For MSW generation, MSW mass and MSW_{mp} after 2000 are collected for comparison because results in Fig. 1(B) show that GDP was accelerated since then. With regard to MSW management, the sanitary management proportion and each strategy contribution are presented in the same time period. Afterward, this study concentrates on source sorting, including the disclosure of its effect on MSW composition, the comparison of models between typical metropolitan and Singapore, and finally the generalization of valuable enlightenment. This study contributes to the comprehensive understanding and promotion the MSW management in China.

2. MSW and main socioeconomic factors in metropolitans

2.1. Brief introduction of the metropolitans

BJ, SH, TJ, and CQ are four province-level municipalities across China that are directly under central government. Both BJ and TJ are located in northern China and belong to the Beijing-Tianjin-Hebei Region, and TJ is about 137 km to BJ. As the capital, BJ is China's political center, cultural center, international communication center, and technological innovation center. SH is located in eastern China and belongs to the Changjiang Delta Region. SH is China's economic center, financial center, trade center, international shipping center, and another technological innovation center. GZ is the capital city of

Guangdong Province, located in southern China, and belongs to the Zhujiang Delta Region. SZ is the sub-provincial city in Guangdong Province, and is about 137 km to GZ. Besides, SZ is one of the six special economic zones established in 1979, and its rapid development is attributed to the national policy of Economic Reform and Opening Up. CQ is a central city located in southwest China and belongs to the Chengdu-Chongqing Region. More information is shown in Table 1. In addition to their heterogeneous locations, land areas in these metropolitans vary distinctly. As can be seen, land area in SZ ranks the last, which is only a fortieth of that in CQ.

2.2. MSW generation

MSW masses of the six metropolitans are shown in Fig. 2(A) from 2002 to 2020, which tend to increase, except for SH during 2014–2016. This is because various policies, e.g., the restriction of excessive packaging and encouragement of green consumption, were implemented around 2012–2013 by SH government to decrease MSW generation. A rebound of MSW mass after 2016 should be ascribed to the weakening of these policies, because the urban population tended to stabilize around 2016 (Fig. 2(B)). The MSW mass in BJ and SH are generally higher as a result of the higher urban population (Fig. 2(B)) and GDP (Fig. 2(C)). MSW mass in TJ is the least because the urban population (Fig. 2(B)) and GDP (Fig. 2(C)) rank amongst the last. With regard to SZ and CQ, they are a little different. MSW mass in SZ ranks third, while its population ranks last and its GDP is comparable to GZ. Both MSW mass and GDP in CQ rank after GZ, while the urban population is almost comparable to that of BJ. All these results indicate that MSW generation is possibly more dependent on GDP than population.

To eliminate the influence of population on the spatiotemporal analysis of MSW mass, MSW_{mp} was calculated, as shown in Fig. 2(D). Based on the value of MSW_{mp}, these metropolitans can be divided into two clusters. The first cluster is composed of BJ, SH, GZ, and SZ, and the remaining two metropolitans constitute the second cluster. MSW_{mp} in the first cluster is mostly within 0.35–0.50 t/a, but 0.15–0.25 t/a for the second cluster. This is not surprising because the metropolitans in the first cluster are first-tier in China. MSW_{mp} in SZ is among the highest, which is possibly attributed to the fact that people in SZ are the youngest. According to the 7th national census, only 5.33% of the people in SZ are >60 years old, whereas the proportions are 19.63%, 23.38%, 11.41%, 21.66%, and 21.87% for BJ, SH, GZ, TJ, and CQ, respectively. One of the lifestyles that the youngsters prefer is take-out service, and SZ is reported to have the highest occupation of take-out service. The take-out service has been condemned for causing plastics pollution (Li et al., 2016). MSW_{mp} in SH tends to decrease in the investigated period, indicating that SH performed well in the reduction of MSW mass. The representative actions to reduce the MSW mass in SH are shown in Table S1 which is in the Electronic Supplementary Material (ESM) in the online version of this paper.

The dependence of MSW generation on GDP is further evidenced by the results in Fig. 2(E). As can be seen, higher GDP per capita (GDP_p) tends to correlate with higher MSW_{mp}. For example, with GDP_p increasing from 0.1×10^4 USD (CQ) to 2.8×10^5 USD (SZ), the MSW_{mp} increases obviously from 0.15 t/a to 0.56 t/a. With equal GDP_p, the MSW_{mp} varies distinctly among the metropolitans. MSW_{mp} in the second cluster is generally less than that in the first cluster. Different from BJ, GZ, and SZ, MSW_{mp} in SH tends to decrease with the increment of GDP_p, which further proved the good performance of a series of MSW mass reduction policies.

3. MSW management and discussion

3.1. MSW composition and the effect of source sorting

Raw composition of the MSW is shown in Table 2. Generally, MSW in all metropolitans is rich in food residual, followed by paper and plastics & rubber. These three compositions are combustible, and in most cases, account for ≥90 wt% of the total MSW, which makes incineration advantageous and gradually predominant in the sanitary treatment of MSW. The MSW in Singapore exhibits similar composition (Zhang et al., 2010). For each of the MSW composition, it is spatially heterogeneous among the metropolitans. The amount of paper and plastics & rubber are obviously higher in SZ, and the food residual proportion is always <45 wt%. The highly-developed commercial environment in SZ makes young people prefer the take-out service to home-made food. Similar to SZ, MSW in GZ contains less food waste, but the plastics & rubber is more abundant. This might be because GZ is a international trade center, and the world-famous "China Import and Export Fair" is annually held there.

Composition of the MSW in the selected metropolitans after source sorting is shown in Table 3. As can be seen, food residual proportion is lower after source sorting. This is ascribed to the separated processing mode under new source sorting rule, which is developed from the traditional mixed incineration mode. The typical scenarios for these two modes are shown in Fig. 3 (Wang et al., 2021b). As can be seen, their major difference is that food waste is classified to the category of exclusive waste-to-resource in the second mode. For food residual proportion in the residual waste, SH ranks the lowest among the three metropolitans, which might indicate the high-quality source sorting.

Source sorting benefits the incineration process mainly by removing food waste, which accounts for the largest proportion of MSW mass (40%–60%) (Ding et al., 2021; Turan et al., 2009). On the one hand, the decrement of MSW mass entering the incinerator is favorable to relieve the burden. On the other hand, food waste removal is favorable to increase the caloricity by avoiding the incomplete incineration and heat loss as a result of H_2O evaporation. Due to the high H_2O content (>70%), food waste is the main H_2O source in MSW (Pham et al., 2015). In this case, exterior carbon is not required to maintain steady incineration. After the food waste is removed, MSW caloricity is comparable to those in developed regions or countries, e.g., EU, USA, and Japan (Fang & Li, 2019). The increased caloricity generates additional heat for electricity, further making up for the MSW incineration cost. Meanwhile, it is reported

Table 1
Detailed information with regard to the metropolitans in China.

Metropolitan	Geographical location	City orientation	Land area (km^2)
BJ	Northern China	Capital/province-level municipality	~16,410
SH	Eastern China	Province-level municipality	~6,340
GZ	Southern China	Province capital	~7,434
SZ	Southern China	Special economic zone	~1,998
TJ	Northern China	Province-level municipality	~11,967
CQ	Southwest China	Province-level municipality	~82,402

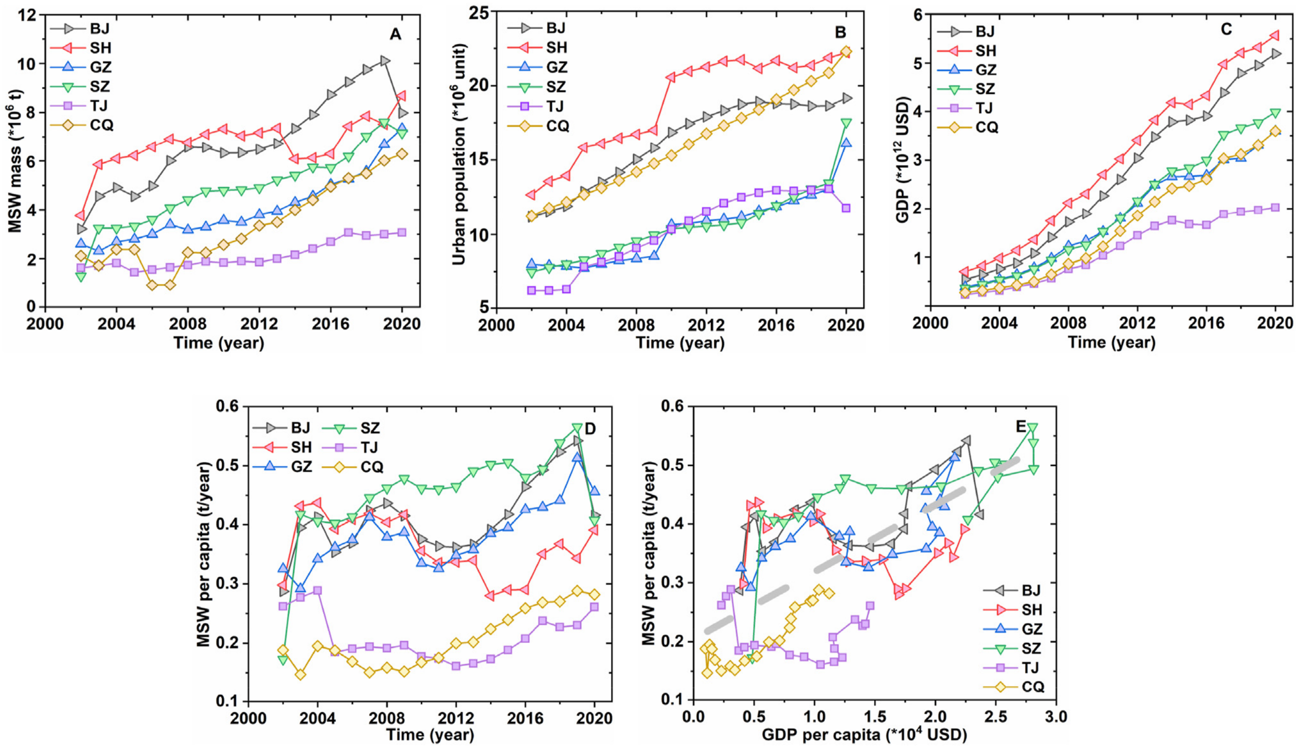

Fig. 2. (A) MSW mass generated, (B) population, (C) GDP, (D) MSW_{mp} as a function of time, and (E) MSW_{mp} as a function of GDP per capita in BJ, SH, GZ, SZ, TJ, and CQ from 2002 to 2020.

Table 2
MSW compositions (wt.%) of the six metropolitans prior to sorting.

Metropolitan	Food residue	Paper	Plastics & rubber	Textile	Wood	Non-combustible	Reference
BJ (2010)	64.9	12.9	15.1	3.1	1.5	2.5	Duan et al. (2020)
BJ (2016)	60.3	17.6	14.1	2.3	0.4	3.6	Wang et al. (2018)
SH (2016)	60.4	11.9	17.6	2.9	2.0	5.4	Ding et al. (2021)
SH (2007)	67.4	9.0	15.7	2.6	1.1	4.3	Xiao et al. (2020)
GZ (2011)	46.5	6.6	25.0	3.2	3.8	14.9	Duan et al. (2020)
GZ (2016)	50.9	12.1	22.8	4.9	1.9	7.4	Tang et al. (2018)
SZ (2011)	42.4	16.3	16.3	2.8	2.9	3.7	Wu et al. (2016)
SZ (2018)	44.0	22.0	18.0	2.0	3.0	8.0	Wang et al. (2016)
TJ (2012)	63.2	11.7	14.6	–	–	10.4	Ding et al. (2021)
TJ (2017)	62.7	15.0	15.0	3.1	–	–	Wang et al. (2021a)
CQ (2005)	59.2	10.1	16.0	6.1	4.2	4.5	Yuan et al. (2006)
CQ (2014)	72.9	9.3	8.4	3.2	1.9	4.2	Zhang et al. (2014)

Table 3
MSW compositions (wt.%) of the selected metropolitans after source sorting[a].

Metropolitan	Food residue	Paper	Plastics & rubber	Textile	Wood	Non-combustible	Reference
BJ (2019)	53.3	15.7	18.9	3.7	0.8	4.85	Wen et al. (2020)
SH (2019)	19.6	23.2	46.8	–[b]	–	–	Xu and Wu (2021)
GZ (2020)	48.7	10.8	26.5	8.2	1.0	4.2	GUMCLEB (2021)
SZ (2018)	56.0	14.0	20.0	3.0	1.0	6.0	Wang et al. (2016)

[a] These metropolitans were selected because they pioneer in source sorting.
[b] The total percentage for textile, wood, and non-combustible is 10.3 wt%.

that source sorting significantly decreases the formation of dioxin in MSW incineration (Shi et al., 2008).

3.2. *MSW management: The unusual SH*

MSW could cause severe water, air, and soil pollution if improperly treated (Levis et al., 2017; Wiedinmyer et al., 2014). Therefore, its sanitary treatment is crucial for city development. The mass of sanitarily treated MSW (m_{eMSW}) increases in each metropolitan (Fig. 4(A)) as a result of the enlargement of MSW sanitary treatment capacity (Q_{MSW}, Fig. S1 in ESM). However, the sanitary treatment percentage of MSW (η_{MSW}) is spatiotemporally heterogeneous, in which the performances of SH and CQ are the least satisfactory. As shown in Fig. 4(B), η_{MSW} of SH and CQ increased

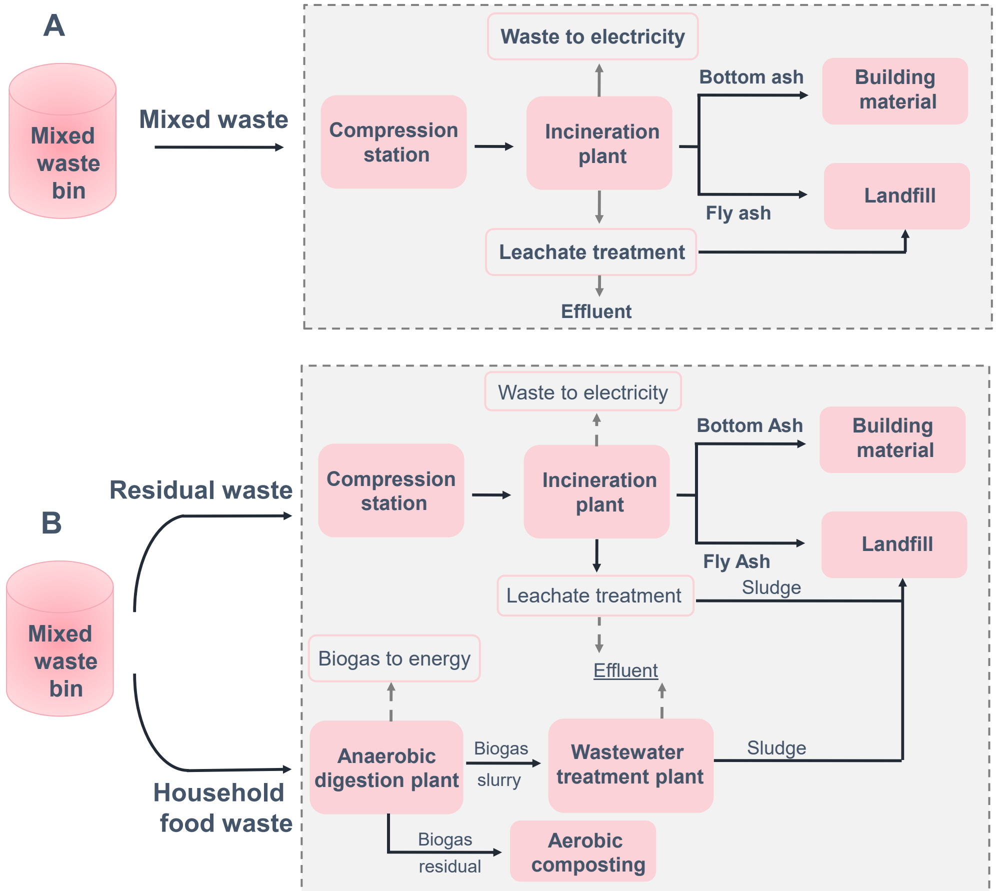

Fig. 3. Scenarios for MSW disposal modes (A) before and (B) after source sorting.

rapidly in the early years, but they were obviously lower than those of the other four metropolitans. Increment of η_{MSW} is possibly ascribed to the improved utilization of Q_{MSW} because Q_{MSW} did not enlarge in either SH or CQ prior to 2012 (Fig. S1 in ESM).

The pollution caused by MSW can be long-time and is directly dependent on the improperly-treated MSW mass (m_{iMSW}). For each metropolitan, m_{iMSW} is shown in the investigated time period in Fig. 4(C). As can be seen, m_{iMSW} in SH is far higher than those in other metropolitans before 2014. Within the whole investigated time period, the overall m_{iMSW} in SH is 3.2×10^7 t, which is one order of magnitude higher than those in BJ with 5.6×10^6 t, GZ with 4.0×10^6 t, SZ with 3.8×10^6 t, TJ with 3.8×10^6 t, and CQ with 9.1×10^6 t, respectively (Fig. 4(D)). All these results indicate that SH is historically lacking in the management of generated MSW, while its economy is pioneering. These historically improperly-treated MSW should be taken seriously, especially for SH.

3.3. Strategies for MSW management: Kuznets curve

Technologies that contribute to the sanitary treatment of MSW in each metropolitan are depicted in Fig. 5(A), 5(B), 5(C), 5(D), 5(E), and 5(F). For BJ and SH, in addition to incineration and landfilling, the contribution of composting cannot be neglected. As can be seen, the composting proportion in BJ was >10% after 2010, and reached 22.4% in 2020. Composting in SH is heterogeneously developed, and its proportion was maximized in 2010 reaching 16.4%. For the remaining metropolitans, incineration and landfilling are two overwhelming technologies, and composting is rarely applied. Since organic waste in the MSW is usually not source sorted, additional sorting equipment or manual works, on a small scale, are required to separate the proper organics prior to composting (Chen et al., 2010). This process generates additional cost and makes composting less competitive in price compared with fertilizer. It is expected that composting will gain further development with better source sorting. If the results in Fig. 2(A) are co-considered, it could be feasibly deduced the heterogeneity of applied sanitary technologies in different regions across China.

Landfilling and incineration are two major technologies responsible for sanitary treatment of MSW. As shown in Fig. 5(G), the landfilling proportion and time are of a uniformly inverted-U-shaped for each metropolitan, indicating that landfilling occupation first increased during the early stage, and then declined at a threshold. Thresholds in most of these metropolitans centered at around 2017–2018, while it is relatively ambiguous for either BJ or CQ. Incineration develops rapidly and accelerates in recent years, especially after 2017. In particular, incineration development in SZ appears to be more radical than in the other five metropolitans (Fig. 5(H)). For example, in the year 2007, 35.8% of the MSW in SZ was incinerated, which is obviously higher than the proportions in BJ, SH, and GZ, which are only 6.5%, 15.6%, and 11.1%, respectively. Incineration is preferred in SZ largely because of its small land area (Table 1). China's first MSW incineration plant was built in SZ in 1988 (Zheng et al., 2014). Incineration is expected to become more prevalent nationwide, accompanied by further shrinking of landfilling in the near further.

The proportions of landfilling and incineration as a function of GDP_p are shown in Fig. 5(I) and 5(J), respectively. For each metropolitan, a similar inverted-U-shaped relationship is observed

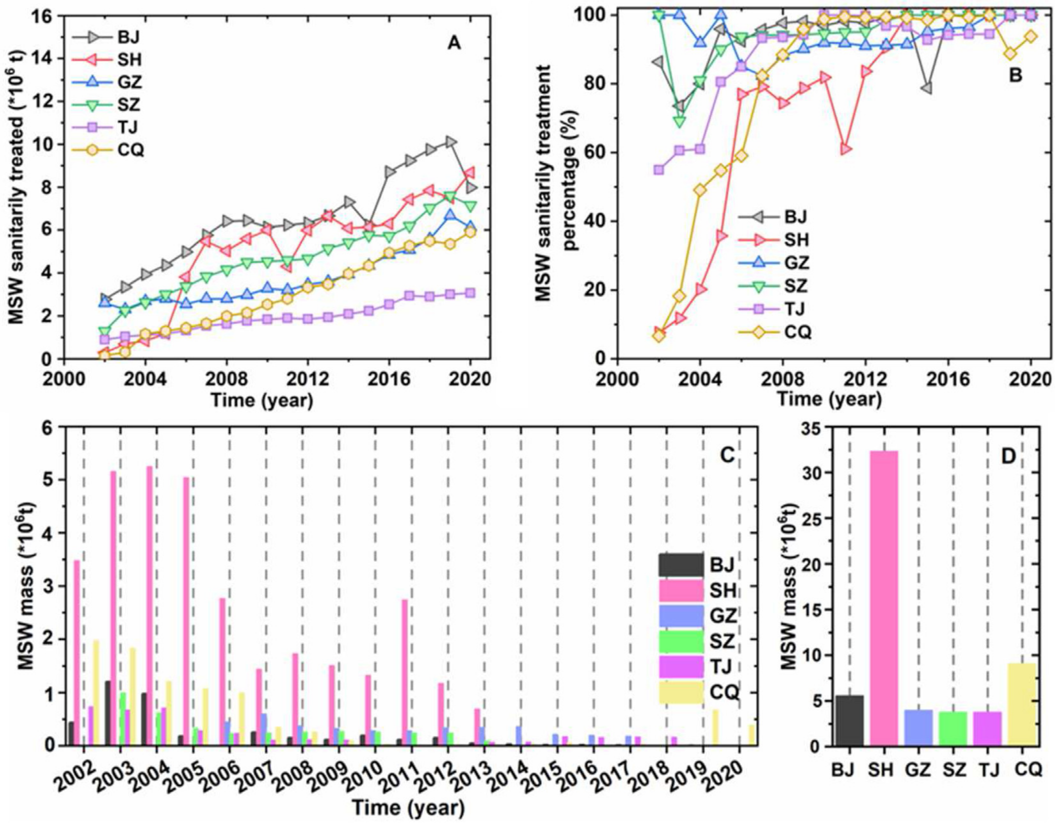

Fig. 4. (A) m_{eMSW}, (B) η_{MSW}, (C) m_{iMSW}, and (D) total m_{iMSW} in BJ, SH, GZ, SZ, TJ, and CQ from 2002 to 2020.

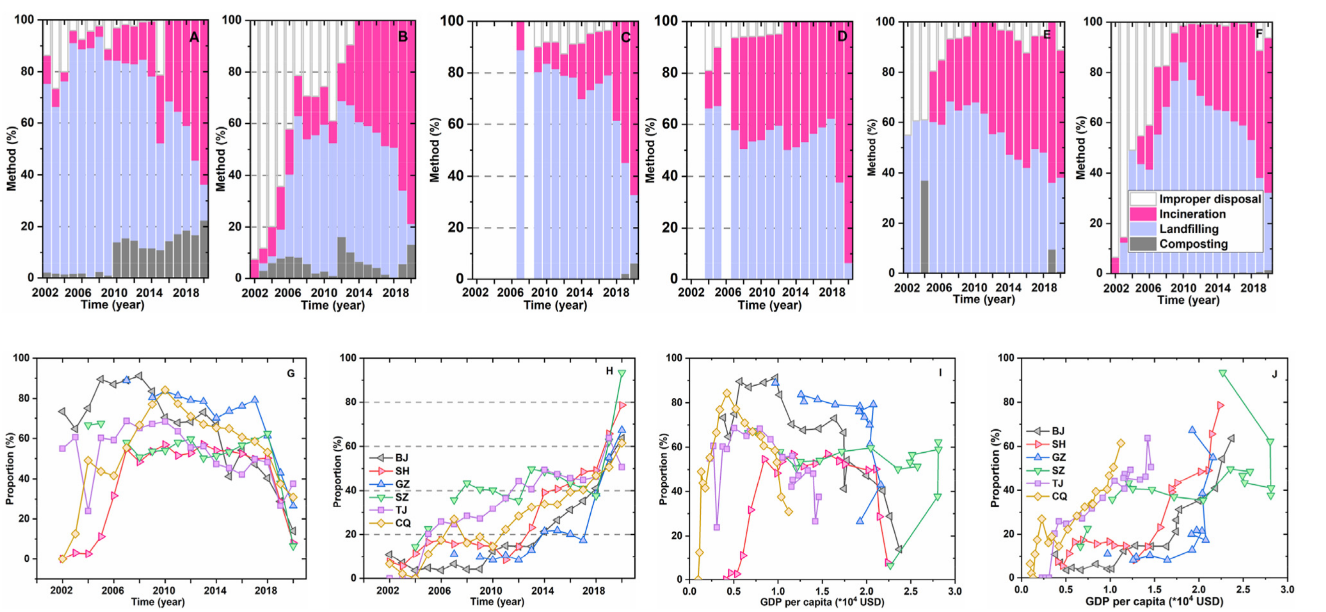

Fig. 5. Proportions of landfilling, incineration, composting, and improper disposal of MSW in (A) BJ, (B) SH, (C) GZ, (D) SZ, (E) TJ, and (F) CQ from 2002 to 2020. Proportions of (G) landfilling and (H) incineration as a function of time, and proportions of (I) landfilling and (J) incineration as a function of GDP per capita in each metropolitan.

between landfilling proportion and GDP_p, conforming to the Environmental Kuznets Curve (EKC). According to the mainstream EKC hypothesis, environmental pressure tends to rise faster than income growth in the early stage of economic development, and then slows down, reaches a threshold, and declines with further income growth (He & Lin, 2019). However, the thresholds vary distinctly. Arranged in descending patterns, the order tends to be SZ, BJ, SH, GZ, TJ, and CQ, and the thresholds in BJ, SH, and GZ are quite close to each other. With regard to incineration, the threshold order is similar (Fig. 5(H) and 5(J)). It is thus feasibly deduced that the economic level is perhaps not a determinant for choosing the technology.

Development of the MSW incineration industry with representative government actions is shown in Fig. 6, and the whole history can be divided into three periods, namely, initial exploration stage, tentative improvement stage, and rapid development stage. With financial and political support from the government for nearly 25 years, these metropolitans are well-prepared for the rapid incineration development after 2011. Therefore, government policy might be the most important factor in MSW management. Incineration benefits city development by reducing the MSW mass by 65%–80% and volume by 85%–90% (Bertolini et al., 2004), which could save land for city development, and transform the MSW into electricity for further usage.

3.4. The experience of MSW management in Singapore

MSW_{mp} in the latest four years is shown in Fig. 7(A), which seems slightly lower to those in the first cluster of metropolitans within the same time period (Fig. 2(D)). Prevention of waste generation has been given priority in sustainable MSW management, especially in developed countries (Soltanian et al., 2022). MSW_{mp} is not extended to a wider time period because with regard to the annual mass of generated solid waste, MSW was not distinguished from other wastes, e.g., industrial waste and construction waste, before 2016. In Singapore, landfilling and incineration are historically the two main technologies for MSW sanitary management, which is quite similar to the situation in China. Their relative proportions are shown in Fig. 7(B). As can be seen, prior to 1978, landfilling was almost the only technology applied. Incineration has been developing rapidly since 1980 when the first incineration plant was built. As a result, incineration and landfilling equally took over the overall MSW sanitary treatment in the year 1986. After rapid development for 20 years, incineration proportion was maximized in 2000 and has been stabilized ever since. To further facilitate sustainable development, recycling has been gradually given priority, which calls for better source sorting. The overall recycling rate reached 60% in 2012, and Singapore plans to further increase it to 70% by 2030 (Fig. 7(C)).

MSW management in Singapore is well developed, and the whole waste collection and transportation system is divided into two sub-systems shown in Fig. 7(D). The two systems are public waste collection system (PWCs) targeting waste generated by the resident, and general waste collection system (GWCs) targeting waste from industrial and commercial activities. Source sorting takes a determinant role in the success of both systems, and most of the work is done by specialized companies. The resident does not need to strictly classify the MSW, but will be sternly fined if waste is illegally dumped. An attempt has been made by Singapore government to classify the MSW in the resident community, which is quite similar to China's current sorting mode, but has made little progress. In this case, the role of the government is crucial to supervise the company activity, as well as support these companies financially and politically if needed. With enhanced sorting, the fee paid for incineration plant can be minimized, and the company can further profit from selling recycled items. Under the incentive of economic profit, the company updated its technology and management for sorting and recycling. Thanks to this system, less than 3.7×10^5 t of the solid residual out of 77×10^5 t MSW after incineration is annually disposed of at Semakau Landfill.

To achieve 70% recycling of the MSW, diverse policies and programs have been formulated and implemented, in most cases, targeting specific waste, e.g., food waste, e-waste, and packaging waste. For example, to better deal with food waste, Singapore is

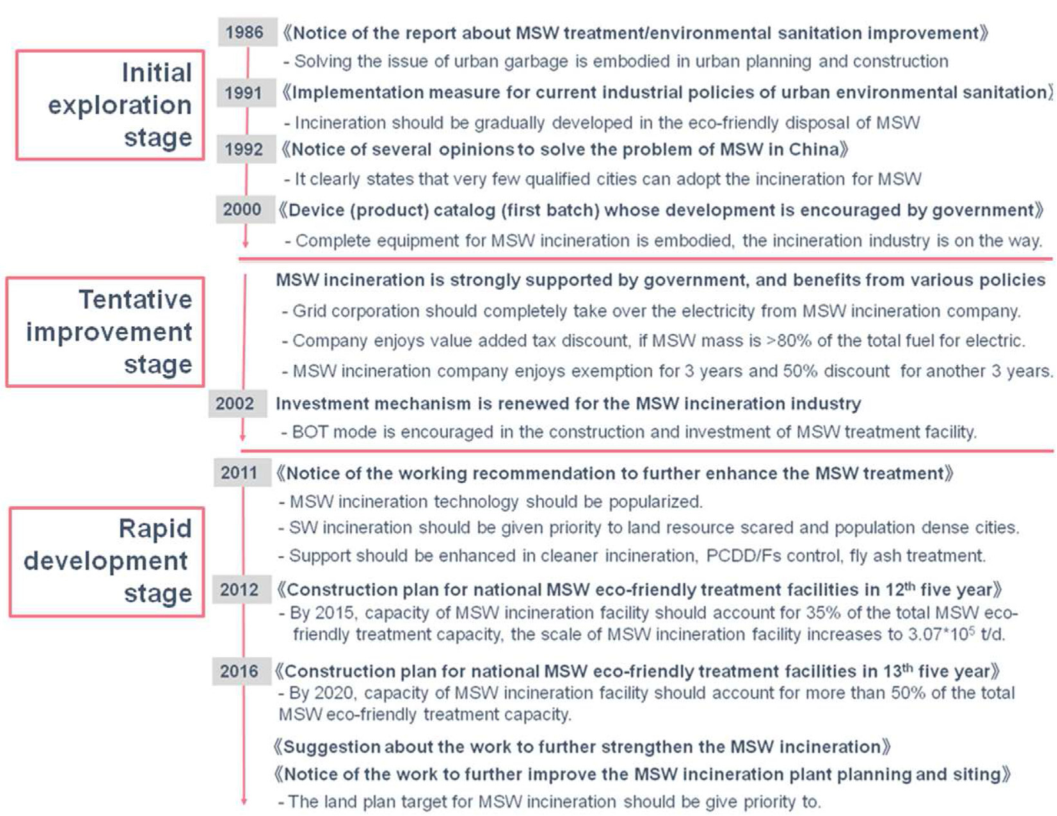

Fig. 6. Development history of MSW incineration with the representative government actions in China.

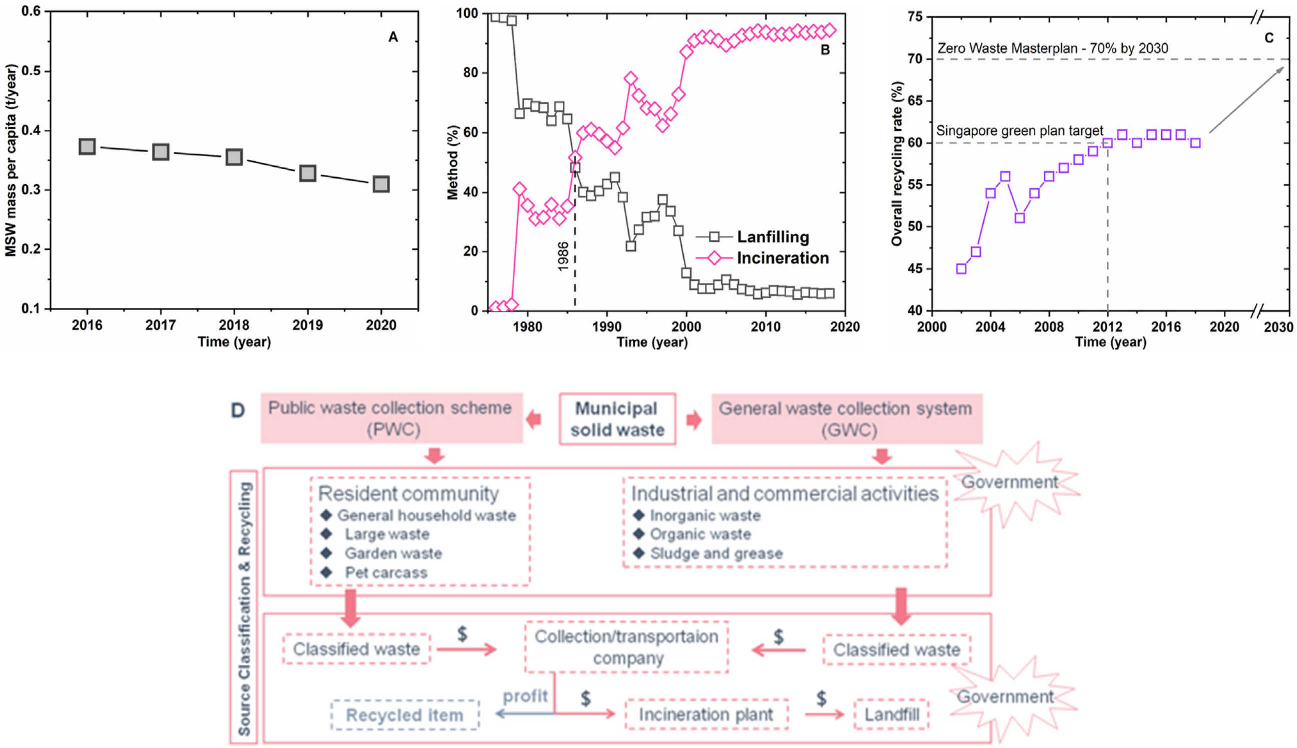

Fig. 7. (A) MSW_{mp}, (B) proportions of landfilling and incineration on MSW disposal as a function of time, (C) MSW recycling rate together with the target in the near future, and (D) MSW disposal mode involving source sorting in Singapore.

now making effort to co-digest it with sewage sludge, but on the premise of source sorting to the most (National Environmental Agency, 2018). To deal with the increasing e-waste, the Regulated E-waste Management System based on extended producer responsibility was implemented to promote e-waste collection and proper treatment (National Environmental Agency, 2023). It is expected that the achievement of this short-term goal is highly dependent on enhanced MSW sorting from the source.

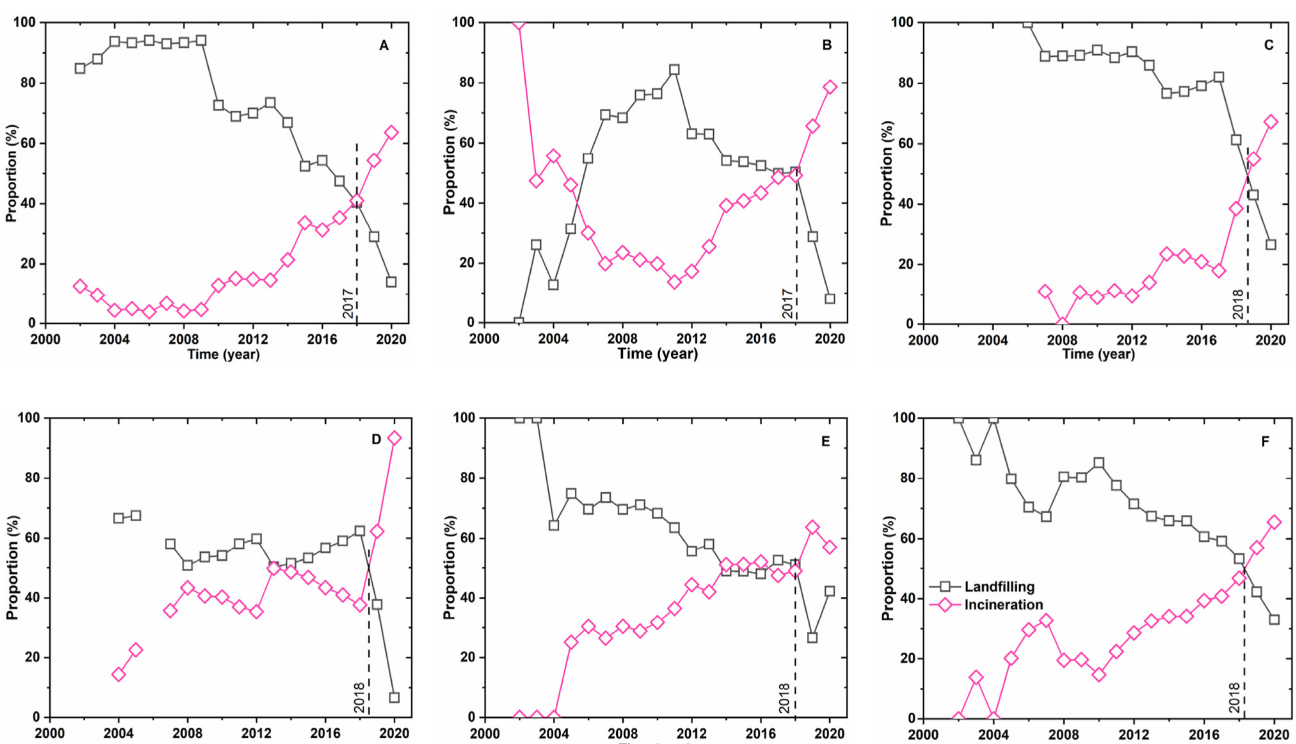

Fig. 8. Proportions of landfilling and incineration on MSW sanitary disposal as a function of time in (A) BJ, (B) SH, (C) GZ, (D) SZ, (E) TJ, and (F) CQ.

Proportions of landfilling and incineration are plotted for the metropolitans as a function of time, and the results are shown in Fig. 8. It is interesting to find that in each metropolitan, the incineration occupation surpasses that of landfilling uniformly in the years 2017–2018, which is consistent with the above-mentioned conclusion that government policy is the most important factor in MSW management. In SH, landfilling was not adopted until 2002 (Fig. 4(B)), which caused its lower occupation than incineration before 2006. In GZ, in both 2008 and 2013, the incineration proportion was quite close to that of landfilling, but did not surpass.

With regard to incineration, the time interval is 6 years in Singapore between the first plant establishment (1980) and the 50% occupation achievement (1986). In comparison, time intervals in the metropolitans are longer. For example, time interval is about 30 years in SZ, which was the location of China's first MSW incineration plant built in the year 1988. Even though the economy develops rapidly, China, including these metropolitans, is still underdeveloped, especially before the year 2000. The socioeconomic status makes China prefer landfilling to incineration for MSW disposal. Singapore spent 14 years enlarging the incineration proportion from 50% (1986) to > 90% (2000). However, the corresponding time is anticipated to be shorter in these metropolitans. For example, in the year 2019, the incineration proportion in SZ reached 93.4%. The metropolitans are well-developed in recent years, which greatly favors the rapid incineration development.

4. Conclusions

In this study, six metropolitans, including Beijing, Shanghai, Guangzhou, Shenzhen, Tianjin, and Chongqing, which are located at four world-class megalopolises across China, are selected to reveal the spatiotemporal heterogeneities of MSW generation and management. Singapore is taken for comparison, for it is a Chinese community and well-known for its outstanding performance in environmental sanitation. It is found that these metropolitans are spatiotemporally heterogeneous in MSW per capita, MSW composition, and sanitary management strategy (landfilling, incineration, and composting). For the first four metropolitans, the MSW per capita is distributed within 0.35–0.50 t/a, but 0.15–0.25 t/a for the remaining two metropolitans. MSW per capita increased with time, especially after the year 2000, because the increment of the GDP per capita has accelerated since then. Results in this study also show that official MSW mass reduction policy is effective to relieve the MSW per capita increment. The development patterns of landfilling and incineration fit to the Kuznets curve well in each metropolitan, and the government policy is more determinant a factor than GDP in sanitary management strategy adoption. With regard to the MSW composition, it is also time- and location-dependent, and the dependencies are explored. Meanwhile, source sorting reduces the proportion of food residue, and its significance in subsequent resource utilization was discussed. Incineration develops much more rapidly in these metropolitans compared to that in Singapore because this technology is mature, and these cities are highly developed. Finally, based on the goal, action, and experience relevant to Singapore MSW management, Chinese metropolitans should be more delicacy in environmental sanitation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by National Natural Science Foundation of China (Grant Nos. 52100152 and 52200208), and Natural Science Foundation of Shenzhen Science and Technology Commission (Grant No. RCBS20210609103644013). Foundation of the State Key Laboratory of Pollution Control and Resource Reuse Foundation (Tongji University, China) (Grant No. PCRRF20013) and the International Postdoctoral Exchange Fellowship Program (Grant No. YJ20200280) are also acknowledged.

Electronic Supplementary Material

Electronic Supplementary Material (ESM): supplementary material is available in the online version of this article at https://doi.org/10.1016/j.cec.2023.100041.

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