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RESEARCH ARTICLE

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Spatiotemporal dynamics of city-level WEEE generation from different sources in China

Abstract China stands as one of the leading producers of waste electrical and electronic equipment (WEEE), facing significant challenges in managing the substantial volumes generated. Despite existing regulations, the informal treatment of WEEE persists in some areas due to inadequate recycling networks at the city level. Consequently, there is a critical need for a detailed geographical mapping of WEEE generation to address improper disposal practices effectively. This study introduces the cMAC – EEEs (city Material Cycles and Manufactured Capital – EEEs) database, providing estimates of WEEE generation across approximately 300 prefecture-level cities from 1978 to 2017. It focuses on five commonly used types of electrical and electronic equipment (refrigerators, air conditioners, washing machines, computers, TVs) originating from three key sources (urban residents, rural residents, enterprises). The findings reveal (1) significant spatial variation in WEEE generation within China, with eastern and central city clusters identified as hotspots, particularly for urban residents and enterprises, while the western region exhibits the highest growth rate in WEEE generation, notably among rural residents. (2) The growth in obsolete computers and air conditioners is prominent, especially in rural areas and among enterprises, whereas the generation of obsolete TVs, washing machines, and refrigerators is leveling off and expected to decrease in some urban areas. (3) Enterprises account for a substantial portion of WEEE generation, though uncertainties exist, necessitating further refinement. The study highlights that less developed regions lack adequate recycling facilities, with specific limitations in refrigerators and air conditioners recycling capabilities. To enhance WEEE management, it advocates for increased interregional collaboration and capacity building in less developed areas. Additionally, the regulation of WEEE from private enterprises requires improvement. At the product level, a greater focus on recycling practices for refrigerators and air conditioners is recommended.

Keywords WEEE, obsolete electrical and electronic equipment, urban mining, waste management, industrial ecology

1 Introduction

China is the largest generator of waste electrical and electronic equipment (WEEE) worldwide. In 2019, it produced 10.1 million tons of WEEE, accounting for nearly 20% of global generation (Forti et al., 2020). As China continues its rapid transition into a modern information society, the growth in WEEE generation is expected to continue. Consequently, managing the recycling and treatment of this substantial volume of WEEE presents a significant challenge for China. Properly recycling and treating WEEEs is important not only for minimizing resource waste and supporting the need for primary resources but also for mitigating health and environmental risks. Despite the implementation of various regulations, the majority of WEEEs in China are

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collected by individual collectors and dealers (CHEARI, 2019). As these collectors and dealers operate without proper oversight, WEEEs often end up in the informal recycling sector where they are inadequately treated. Consequently, China has a low formal recycling rate (Zeng et al., 2017), resulting in significant resource losses and adverse effects on human health and the environment (Baldé et al., 2017; Duan et al., 2018; Li and Achal, 2020). It is therefore crucial to establish a regulated and traceable WEEE collection and recycling system in China.

A comprehensive collection and recycling system necessitates the accurate assessment of WEEE generation. Numerous studies have conducted time-series assessments of WEEE generation at both the national (Habuer et al., 2014; Duan et al., 2016; Zeng et al., 2016; Zeng et al., 2021) and provincial levels (Li et al., 2015; Wang and Mishima, 2019; Sun et al., 2022), as well as specific cities such as Beijing (Liu et al., 2006; Gu et al., 2016), Zhejiang (Cao et al., 2016), Nanjing (Zhang et al., 2011), and Chongqing (Li et al., 2011). Based on this research, China has developed a hierarchical management system for WEEE recycling that operates on a provincial administration basis, aiming to establish local disposal capacities in line with provincial generation. As of 2015, China has certified 109 enterprises across 29 provinces (United Nations, 2020) and has improved the formal recycling rate to 35%, matching the levels seen in developed countries (Zeng et al., 2017).

However, the current collection system is primarily market-driven, resulting in a discrepancy between WEEE generation and disposal capabilities within administrative boundaries. A significant portion of WEEE flows across city and provincial boundaries and ends up in the informal sector, impeding progress toward achieving higher formal recycling rates (Tong et al., 2018). Consequently, there is a need for a more precise national collection system that incorporates a cooperative mechanism among provinces and cities, as well as a more rational spatial layout of national disposal capabilities (Abbondanza and Souza, 2019). In 2020, China issued a plan to enhance the WEEE collection system, emphasizing the optimization of the system at the city level. Therefore, it is crucial to assess and monitor WEEE generation and collection at the city level, an area that has been underexplored in research.

Furthermore, there is a lack of studies examining the quantities and types of WEEE from different sources. The three primary producers of WEEE are urban households, rural households, and enterprises. Enterprises generate WEEE predominantly in the form of computers, air conditioners, and printers, which differ from the types produced by urban and rural households. Compared to urban residents, rural residents are more prone to accumulating outdated electrical and electronic equipment (EEE) in their homes or selling it to individual collectors and dealers (Cao et al., 2016; Sun, 2017). Enterprises generate WEEE on a more consistent basis and are more willing to collaborate with formal disposal enterprises to promote a green corporate image (Qu et al., 2013). Given these differences in WEEE recycling attitudes and behaviors (Qu et al., 2013), it is crucial to establish specific collection channels and mechanisms for different sources (Nowakowski and Mrówczyńska, 2018; Gonda et al., 2019). However, few studies have distinguished the various sources of WEEE in China, particularly those generated by enterprises (Song et al., 2016), calling for the development of precise local management systems.

To address the aforementioned gaps in the literature, our primary objective is to determine the generation of at the city level and estimate the amount produced by different producers. However, accurately assessing city-level WEEE generation presents a significant challenge. Various methods, at least 10 in total, have been employed to estimate WEEE generation. Most of these methods rely on sales data, while a few are based on stock data (Zeng et al., 2016). Although sales data are readily accessible and reliable at the national level, obtaining accurate data becomes more difficult and less reliable when it comes to smaller geographical resolutions due to cross-border sales. On the other hand, the quality of stock data does not diminish with increasing geographical resolution. Therefore, we utilize stock data to estimate WEEE generation at the city level (Zhang et al., 2011).

To determine the spatiotemporal distribution of WEEE at the city level in China, we establish the cMAC – EEEs (city MAterial Cycles and MAnufactured Capital – EEEs) database, which includes over 100000 stock data points spanning from 1978 to 2017. This database comprises five types of EEEs: televisions (both color and black-and-white), washing machines, refrigerators, air conditioners, and computers (desktops and laptops). These types of EEEs constitute the initial batch of products listed in the WEEE Catalog released by the Chinese government in 2010 (MIIT, 2010). Although China has subsequently released a second batch of the WEEE Catalog in 2014 (MIIT, 2014), expanding it to include 14 types of products, this study focuses solely on these five types of EEEs due to their widespread use in households and businesses, as well as their substantial environmental impact. This study is the first to present a comprehensive map of WEEE generation over such an extensive period and at such a high resolution. This approach enables us to uncover the spatial development patterns of WEEE generation throughout China and provides valuable data for the development of a more precise national-level WEEE management system. Furthermore, examining the spatial distribution of disposal capabilities allows us to identify specific aspects of WEEE management that require greater attention.

2 Model and data

2.1 Household appliance stock and WEEE generation calculation model

To calculate the quantity of a particular type of WEEE generated in a specific city and year, it is crucial to first determine the stock volume for that year. Subsequently, WEEE generation can be estimated based on the stock data and the stock and lifespan model (Müller et al., 2009; Binder et al., 2001; Walk, 2009). Considering that WEEE originates from three sources, namely urban residents, rural residents, and enterprises, the equation for calculating the total stock of a product in a city and year t is as follows:

$$S(t)=\sum_{i=1}^{3}S_i(t)=\sum_{i=1}^{3}P_i(t)\times H_i(t), \quad (1)$$

where $S(t)$ is the total stock of EEE in a city in year t. $S_i(t)$ represent stocks in urban households, rural households, and public and private enterprises. $P_i(t)$ is the EEE penetration of urban households, rural households, and public and private enterprises, which is the number of EEEs per household or the number of EEEs per employee. $H_i(t)$ is the urban and rural household number or employee number.

Based on the stock and lifespan model, WEEE generation can be calculated according to Eqs. (2) and (3):

$$F^{\mathrm{in}}(t)=(S(t)-S(t-1))+F^{\mathrm{out}}(t), \quad (2)$$

$$F^{\mathrm{out}}(t)=\sum_{k=1}^{M}F^{\mathrm{in}}(t-k)\times d(k), \quad (3)$$

where $F^{\mathrm{in}}(t)$ and $F^{\mathrm{in}}(t-k)$ are the product inflows entering society in year t and year $t-k$, respectively. $F^{\mathrm{out}}(t)$ is the outflow of obsolete products in year t, $S(t)$ and $S(t-1)$ are the stocks of products in year t and year $t-1$, respectively. M is the maximum lifetime of the product, and $d(k)$ is the lifetime distribution density value in the k years old of the product, which can be represented as a probability density function. In order for the model to be calculable, a series of product inflow data, or at least data for one year, is necessary. If such data are unavailable, it is assumed that the product inflow for the initial year is zero. Therefore, stock data has been collected since 1978, when EEEs were rarely present in China.

2.2 Time-series database of EEE stocks in China's cities

To establish the cMAC-EEEs database, data on the penetration of five types of EEEs in households (both urban and rural) and enterprises, as well as the number of households and employees, were collected from 1978 to 2017 in 301 cities. More detailed information is provided below.

2.2.1 Study area and three sources of WEEE

The study area includes China's mainland, which consists of 34 provincial regions and further divided into 363 regions, including 4 municipalities, 294 prefecture-level cities, 7 prefectures, 30 autonomous prefectures, 3 leagues, and 25 province-controlled divisions (National Bureau of Statistics of China (NBSC), 2017). The municipalities and prefecture-level cities serve as the primary administrative units in China, accounting for 94% of the total population and 97% of the total GDP. Since the stock of EEEs is primarily influenced by population and GDP (Li et al., 2020a), it is reasonable to assume that the majority of EEE stocks in China are concentrated in these areas. For regions with limited data, the remaining cities within a province are treated as a single region in order to estimate values based on available city- and province-level data. As a result, China is ultimately divided into 301 cities. Please refer to Table S1 for a complete list of these cities. Among them, 163 cities comprise 13 major city clusters (see Supplementary Information [SI] section 1.2 for China's definition of a city cluster) that serve as the economic and population growth centers in China. The city cluster list is presented in Table S2.

For each city, there are three sources of WEEE: urban households, rural households, and enterprises. Urban or rural households refer to families residing in either urban or rural areas of a city. Household EEEs are disposed of by the households themselves and often end up in the informal recycling sector. Enterprises include all legal entities in urban and rural areas, and can be categorized into public and private companies. Public companies include state-owned or collectively-owned enterprises, as well as government agencies, institutions, and social organizations that rely at least partially on public funds. EEEs used by these enterprises are considered state-owned property, and their disposal procedures are regulated by central or local governments (NBSC, 2002/04/19). In most cities, WEEE generated by public enterprises must be sent to formal disposal enterprises. Private enterprises, on the other hand, are established by individuals or investors rather than the state or collectives. EEEs used in private enterprises are disposed of by the enterprises themselves, and there is generally a lack of standardized disposal practices. However, due to a lack of available information, this study does not differentiate between public and private enterprises.

2.2.2 Data collection and estimation

Household data. EEE penetration data and household number data for both urban and rural areas can be obtained from the statistical yearbooks of cities. We collected this data from the statistical yearbooks of nearly 300 prefecture-level cities, as well as their provincial yearbooks, covering a period from 1978 to 2017. To obtain urban and rural

EEE penetration data for cities, we needed to gather over 140000 data points, but approximately half of these data points were missing. Fortunately, most of the missing data pertained to years prior to 2000 and accounted for only about 20% of the total. We employed two principles to estimate the missing data: (1) the total EEE stock in cities within a province should match the provincial-level data, and (2) the proportion of a city's stock within the province should remain relatively stable from year to year. Data for household numbers in cities' yearbooks were comparatively complete, and we utilized interpolation methods to estimate any missing data.

Enterprise data. Air conditioners and computers are the most widely used EEEs in enterprises. To estimate the city-level office penetration of computers, we rely on the office penetration data at the provincial level, which can be found in the statistical yearbooks. These yearbooks are considered the most authoritative and detailed source of data. Unlike computers, the office penetration data of air conditioners is not officially reported. Instead, it is based on a survey conducted in Beijing (Gu et al., 2016). It is worth noting that the temperatures in Beijing during summer are generally lower than in many southern cities. Since the penetration of air conditioners is highly influenced by temperature (Davis and Gertler, 2015), the stock of air conditioners in enterprises may be underestimated. Moreover, large facilities like shopping malls and office buildings use central air conditioning systems with high cooling capacities, often exceeding 14000 W. However, these stocks are not included in the catalog of WEEE recycling in China (MIIT, 2010). Therefore, we do not consider these stocks in our research. The EEE stocks used in enterprises can be calculated by multiplying the number of employees.

2.3 Lifespan distribution of EEEs

The lifespan distribution of EEEs significantly affects the calculation of WEEE generation. There are various definitions of lifespan (Murakami et al., 2010), but for the estimation of WEEE generation, the generally used lifespan is service lifespan A (Fig. 1). However, in China, around 30% of out-of-use products are stored at home, leading to a longer time before they reach collection sites (Chi et al., 2014). As this study aims to provide data for supporting the collection system, service lifespan B is more suitable than service lifespan A (Fig. 1). Service lifespan B refers to the time period starting from the production of EEEs to their storage at home after use. The difference between service lifespan B and A is known as the "storage period." Unfortunately, there is no available data regarding the service lifespan distribution of EEEs in China (Zeng et al., 2016). However, a recent survey by Huang et al. (2020) examined the lifespan of EEEs from their usage until they are shipped to disposal facilities, which includes the collection span. Since the collection span is typically less than one year, Huang's survey provides an approximation of service lifespan B, which can be utilized in this study. Although the survey was conducted in 10 cities and showed the existence of regional differences in lifespan, only national-level lifespan data were reported. Consequently, we employ these lifespan data in our research.

Most televisions, refrigerators, washing machines, and air conditioners in China are recycled after 11–19 years of use. The lifespan of computers is 11–17 years, which exceeds the lifespan data used in other studies (Duan et al., 2016; Zeng et al., 2016; Zeng et al., 2021). A small percentage, more than 5% of EEEs last longer than 20 years. The lifespan distribution model of this research is presented in Figure S1.

3 Results

3.1 WEEEs in China continue to increase, and some types are approaching the peak

The generation of WEEEs in China has consistently risen alongside the increase in EEE ownership since 1978 and

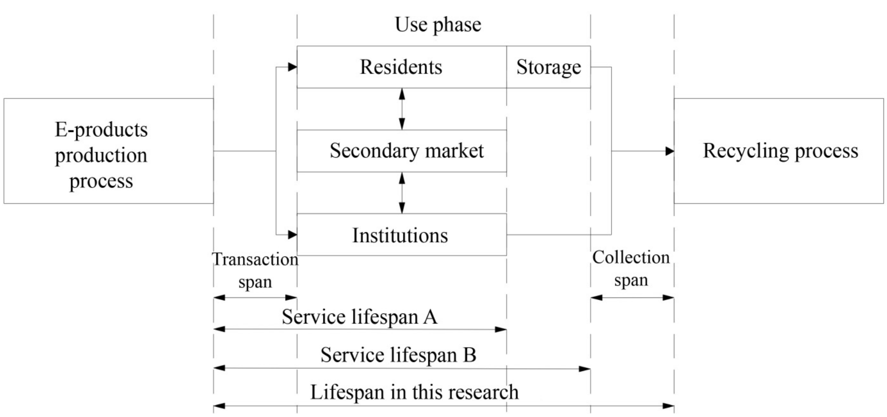


Fig. 1 Definition of lifespan in this research.

has not yet reached its peak (Figs. 2 and S3). However, the annual growth rate has declined significantly (Figs. 2(b) and S2). In 2017, China produced 117 million units of WEEE, twice the amount generated in 2000. The growth rate remained stable at around 8% from 2003 to 2014, but decreased to below 7% thereafter. The primary EEEs used by Chinese households are televisions, washing machines, and refrigerators. Obsolete televisions, both color and black-and-white, have nearly reached saturation, accounting for the highest proportion (37% in 2017), followed by washing machines (21% in 2017) and refrigerators (11% in 2017). Although black-and-white televisions were discontinued from the market many years ago, a small number still remain due to their long lifespan, totaling approximately three million units. Air conditioners and computers are relatively newer types of WEEEs that Chinese households began adopting after the 1990s. Over time, air conditioners and computers have become increasingly significant, constituting 16% and 15% respectively of the total WEEE in 2017.

Although the overall WEEE generation in each city shows a growth trend, the generation of obsolete televisions, washing machines, and refrigerators is approaching its peak or has already started to decline in certain cities (Figures S4–S8). In 2017, nearly 100 cities exhibited a decreasing trend in obsolete television generation. Obsolete televisions had the lowest median growth rate (1%) in 2017, followed by washing machines (5%) and refrigerators (15%). On the other hand, the generation of obsolete air conditioners and computers continued to rise in all cities, with median growth rates of 16% and 17% respectively, and over 260 cities maintained double-digit growth rates (Figures S2 and S9). Therefore, air conditioners and computers have emerged as the primary drivers of WEEE generation.

3.2 Eastern cities have high WEEE density while western cities were growing fast

During the study period, the concentration of WEEE

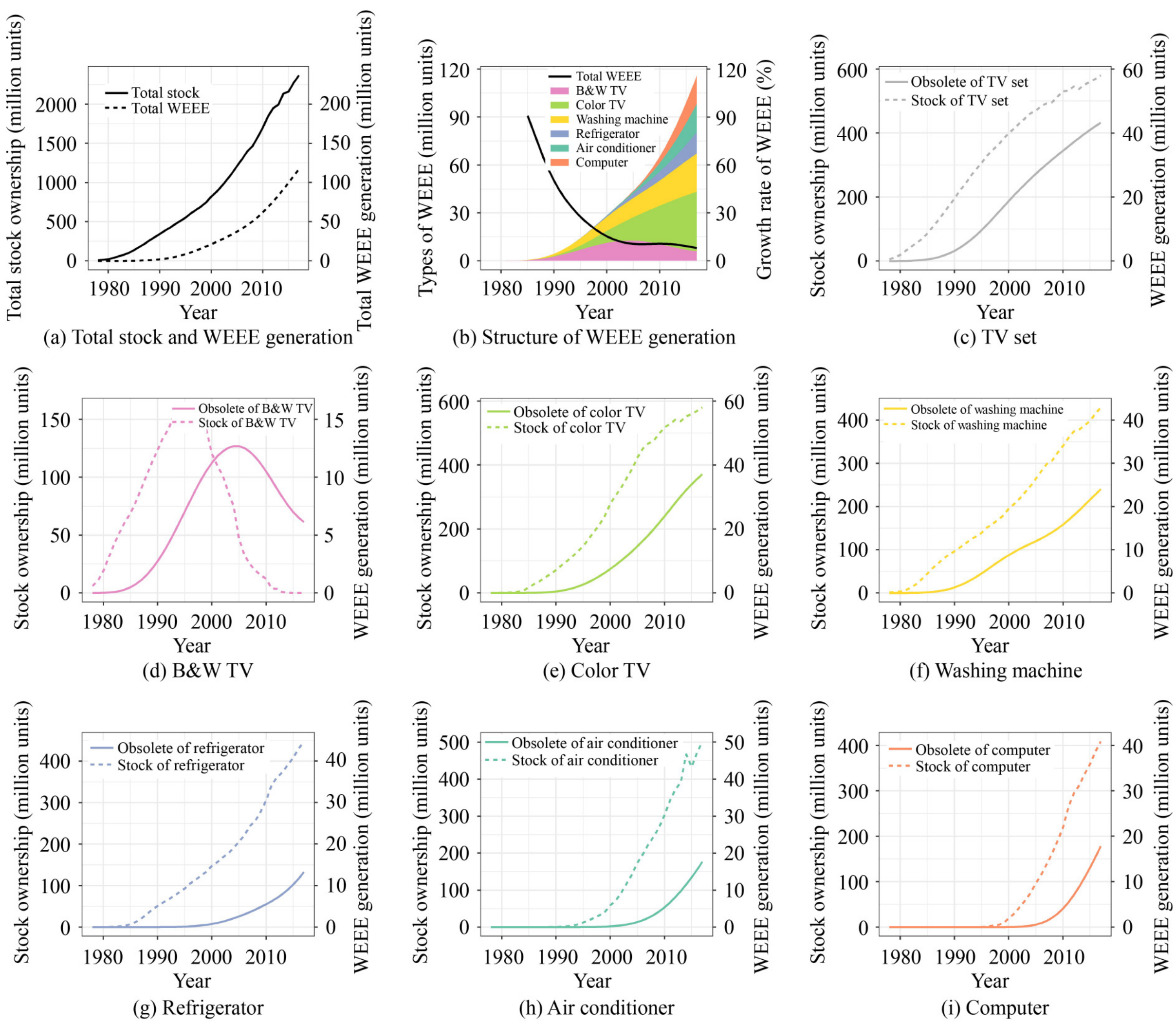


Fig. 2 Scale and structure of EEE stock and WEEE generation in China from 1978 to 2017.

gradually increased in nine city clusters located in the eastern and central regions of China (Fig. 3(a)). These clusters include Jing-Jin-Ji, the Yangtze River Delta, the Pearl River Delta, the Chengyu city cluster, the Middle Yangtze River city cluster, the Central Plain city cluster, the Shandong Peninsula city cluster, the western coast of the Taiwan Strait, and the Guanzhong city cluster. The cities of Beijing, Tianjin, Shanghai, and Guangzhou, which are all major cities with large populations and high economic output, have the highest WEEE generation density (per 1000 km^2). In general, the eastern and central regions of China have significantly higher WEEE generation density, making them key areas for the establishment of WEEE collection networks and municipal waste management systems.

The cities with higher growth rates of WEEE generation

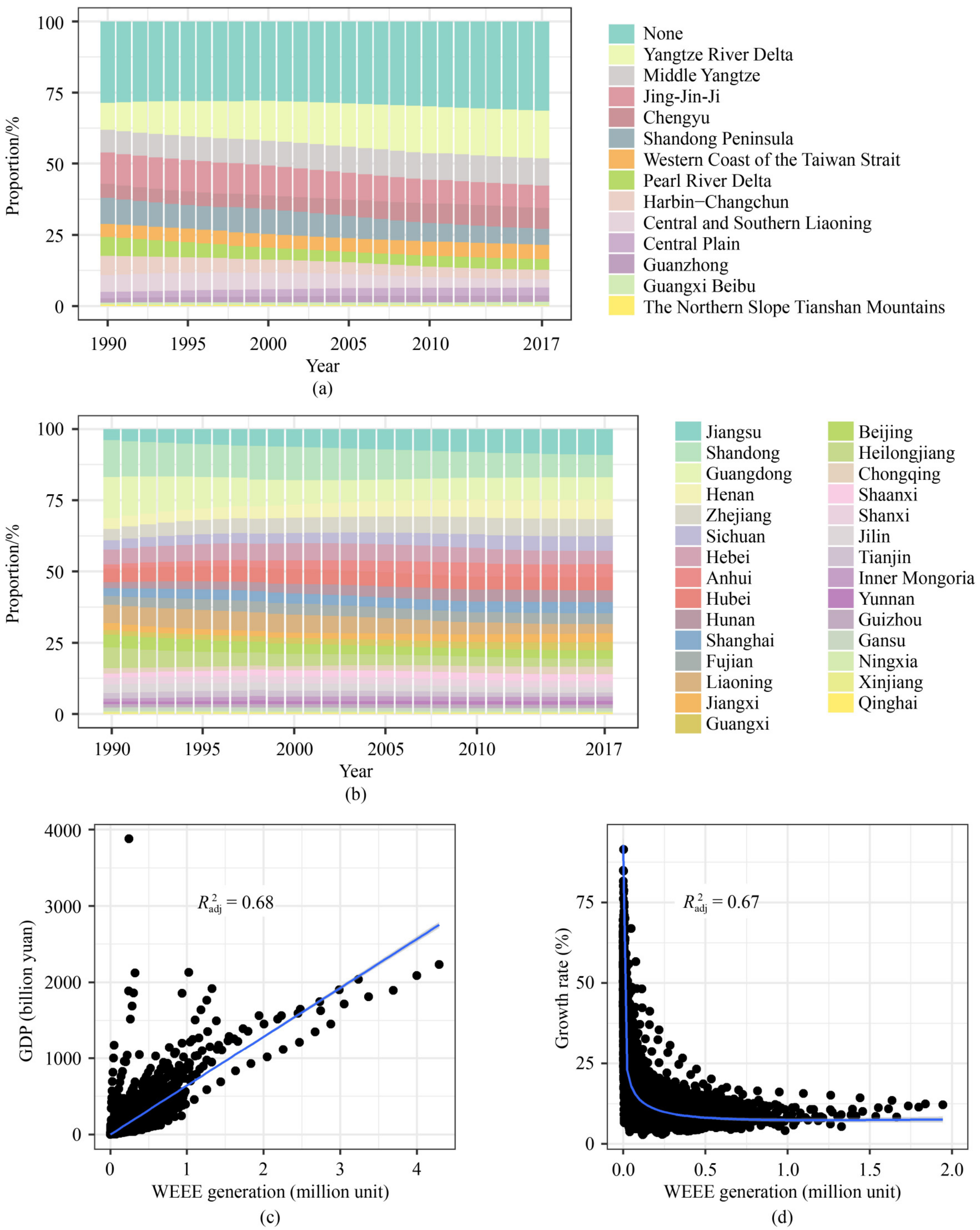


Fig. 3 (a) WEEE generation in provincial level, (b) WEEE generation of city clusters, (c) relationship between WEEE generation and GDP, and (d) relationship between WEEE generation and its growth rate in 2017.

are primarily located in western China, where there are many less developed provinces such as Yunnan, Guangxi, Guizhou, Ningxia, and Gansu. Additionally, developing cities in the eastern and central regions of China, such as Huai'an, Dezhou, and Suizhou, also exhibit high growth rates (Fig. 3(b)). Eastern cities experienced slower growth initially, followed by central cities, whereas the fastest growth is observed in western cities, despite their lower WEEE generation density. WEEE generation in less developed cities is catching up with that of developed cities, which could pose new challenges for waste collection and management systems in these less developed areas in the future.

The findings reveal that as cities experience economic development, their WEEE generation also increases (Fig. 3(c)), despite the slower growth rates (Fig. 3(d)). These relationships are further supported by the calculated correlation coefficients (Figure S10). As poverty levels have decreased over the past three decades in China (Zhang et al., 2020), people in less developed regions now have greater affordability for EEEs (Biggeri and Bortolotti, 2020). Consequently, WEEE generation is rising in both developed and less developed cities. However, the growth patterns of obsolete EEEs follow logistic curves, which include growth, saturation, and decline phases (Althaf et al., 2019). Economically developed cities reach saturation in WEEE generation, while less developed cities continue to experience growth. This leads to a convergence of WEEE generation density among different regions (Figure S11).

3.3 Urban areas are the main source of WEEE while rural areas and enterprises have high growth rates

Urban areas have historically been the primary generators of WEEE, accounting for 63% of the total (Fig. 4(a)), 53% of obsolete TVs, 64% of washing machines, 68% of refrigerators, 79% of air conditioners, and 69% of computers in 2017 (Figs. 4(b)–4(f)). However, the proportion of WEEE generated by urban areas has been steadily decreasing, while the proportions from rural areas and enterprises have been increasing. In 2017, 5% of the total WEEE, 10% of obsolete air conditioners, and 21% of obsolete computers originated from enterprises.

The amount of WEEE generated by urban areas, rural areas, and enterprises has consistently increased for each city from 1978 to 2017 (Figs. S12–S26). The median growth rates in 2017 for WEEE generated by urban areas, rural areas, and enterprises were 7%, 6%, and 21%, respectively (Figure S27). Enterprise-generated WEEE experienced the fastest growth due to the development of the tertiary industry and informatization. Rural areas exhibited a slightly lower growth rate compared to urban areas. This is attributed to a declining trend in obsolete TVs observed in over 160 rural areas versus only 60 urban areas. However, most urban areas still experienced a 2%–5% growth rate. Growth rates for washing machines and refrigerators were higher in rural areas than in urban areas. Specifically, nearly 250 rural areas maintained double-digit growth rates for refrigerators, with a median growth rate of 19%, compared to only 5% in urban areas. Rural areas also had the highest growth rates

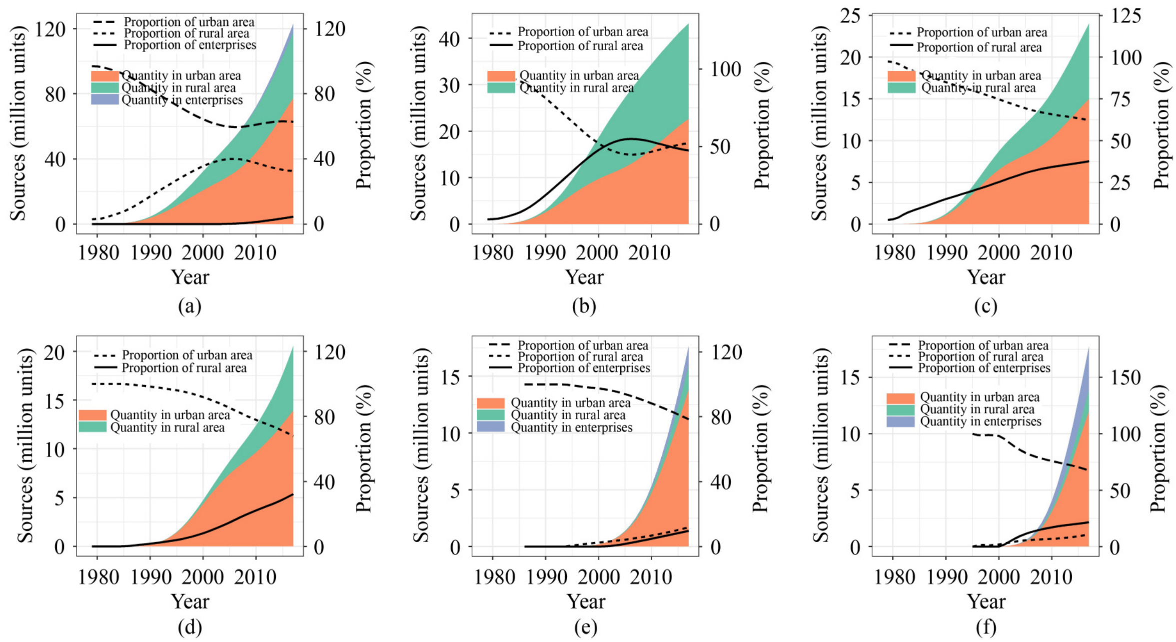


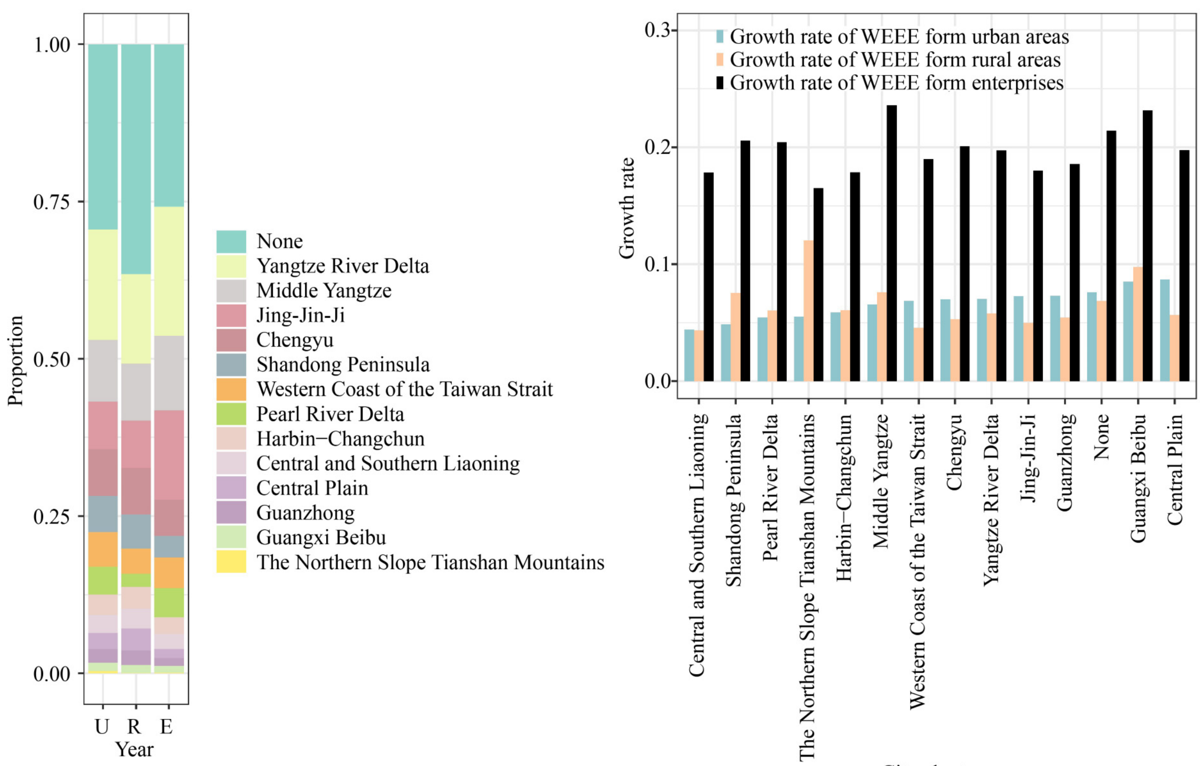
Fig. 4 Growth trends in (a) total WEEE, (b) obsolete TVs, (c) obsolete washing machines, (d) obsolete refrigerators, (e) obsolete air conditioners, and (f) obsolete computers generated from urban areas, rural areas, and enterprises from 1978 to 2017.

for air conditioners and computers, followed by enterprises. More than 130 rural areas exhibited growth rates above 10% for obsolete air conditioner and computer generation, with median growth rates of 28% and 37%, respectively. Likewise, nearly 290 cities had double-digit growth rates for these two types of waste generated by enterprises, with median growth rates of 22% and 20%. In urban areas, the median growth rates were 14% and 15%. Consequently, we predict that WEEE generated by rural areas and enterprises will continue to occupy a greater proportion in most cities.

3.4 Inconsistent spatial distribution of WEEE from different sources

WEEE generated by urban families, rural families, and enterprises exhibits different spatial distributions (Fig. 5(a)). In urban areas, the spatial distribution of each type of WEEE remains generally consistent. Notably, coastal cities such as Shanghai, Xiamen, Shantou, Wuxi, Shenzhen, Guangzhou, Beijing, Nanjing, Suzhou, Tianjin, and Foshan present the highest density of WEEE generation. Moreover, urban areas within the Middle Yangtze River city cluster, and Chengyu city cluster also demonstrate higher WEEE generation density. On the other hand, WEEE generated by rural areas primarily concentrates in cities within the Yangtze River Delta region, including Nantong, Taizhou, Shanghai, Zhenjiang, Yangzhou, Wuxi, and Zhoushan. These cities additionally exhibit the highest levels of rural economic development. Furthermore, rural areas in coastal cities and the Middle Yangtze River city cluster also manifest elevated WEEE generation levels. Notably, the Pearl River Delta, Chengyu region, and Middle Yangtze River are key areas for obsolete TV generation. Regarding enterprise WEEE generation, it is prominently concentrated in leading cities such as Shanghai, Beijing, Wuxi, Xiamen, Nanjing, Guangzhou, Shenzhen, Wuhan, and Suzhou, including both air conditioners and computers. These cities represent the key industrial and commercial centers in China, as noted by the National Bureau of Statistics of China (NBSC, 2020). The development level of the service industry remarkably influences WEEE generation from enterprises.

The spatial distribution of growth rates in WEEE generation varies significantly among urban areas, rural areas, and enterprises (Fig. 5(b)). The urban areas experiencing the highest growth in WEEE generation are typically less developed cities within city clusters or cities near these clusters. Examples include Wuhu, Nantong, Changzhou, and Huai'an in the Yangtze River Delta; Longyan and Shanwei on the western coast of the Taiwan Strait; Jiujiang, Chenzhou, and Suizhou in the Middle Yangtze River city cluster; Meishan, Guang'an, and



(a) WEEE generation of city clusters

(b) Growth rate of WEEE for city clusters

Fig. 5 WEEE generated from urban areas, rural areas, and enterprises and their growth rates in city clusters in 2017.

Suining in the Chengyu city cluster; Xuchang, Zhoukou, and Kaifeng in the Central Plain city cluster; and Shangluo, Dingxi, and Qingyang in the Guanzhong city cluster. The growth in WEEE generation in urban areas primarily arises from air conditioners and computers. The spatial distribution of these types of WEEE mirrors that of the total WEEE generated by urban areas. In rural areas, the highest growth rates of WEEE generation are observed in Qinghai, Xizang, Guangxi, Guizhou, and Yunnan, as well as in some less developed cities within developed provinces, such as Dongying, Laiwu, and Dezhou in Shandong; Xiangtan and Yongzhou in Hunan; and Maanshan in Anhui. Generally, less developed cities have lower WEEE generation overall but higher growth rates of WEEE generation for both urban and rural areas (Figure S28). The growth rate of WEEE generated by enterprises exhibits a more even spatial distribution, with around 24 provinces having cities with growth rates exceeding 20% for enterprise WEEE.

The quantity of WEEE generated by enterprises is influenced by the number of employees and the level of informatization. In general, industries with a larger workforce have higher outputs. Tertiary industries, such as information transmission, software and information technology, scientific research and technical services, and education, have the highest level of informatization, followed by the secondary industry (manufacturing) and the primary industry. Consequently, the output of tertiary industries has the most effect on enterprise WEEE generation, while the primary industry has the least effect (Figure S29). As a result, economically developed cities, especially those with high outputs from tertiary industries, exhibit higher levels of WEEE generation from enterprises. Given that each province has cities with high GDP growth rates, the spatial distribution of WEEE generation growth for enterprises is also fairly even.

4 Discussion

4.1 WEEE generation in China has high spatial heterogeneity

Our analysis of the spatiotemporal distribution of city-level WEEE generation in China has revealed interesting patterns of WEEE generation, as outlined below.

The generation of WEEE in China exhibits significant spatial heterogeneity. The areas with the highest concentration of WEEE generation are primarily located in city clusters with high population density and economic output. Among these areas, the Yangtze River Delta stands out as having the highest density of WEEE generation across urban areas, rural areas, and enterprises. This can be attributed to its high level of development in both urban and rural areas, as well as its well-established manufacturing and service industries. Other hotspots for WEEE generation, particularly from enterprises, include the Jing-Jin-Ji city cluster, the Pearl River Delta, and the Western Coast of the Taiwan Strait. In terms of "old" EEEs such as TVs, washing machines, and refrigerators, the city clusters in central China, including the Chengyu city cluster, Central Plain city cluster, Middle Yangtze River city cluster, and Shandong Peninsula city cluster, are also major contributors to WEEE generation. Generally, eastern China exhibits the highest density of WEEE generation, followed by central and western China. These specific city clusters should be prioritized for the implementation of WEEE collection and recycling systems.

However, there is a narrowing of the spatial differences in WEEE generation in China due to the rapid growth of WEEE in less developed areas, such as Yunnan, Guangxi, Guizhou, Ningxia, and Gansu in western China, as well as certain less developed cities in eastern and central China, particularly in rural areas. The developed regions, despite having high levels of WEEE generation, demonstrate low or even negative growth rates. On the other hand, less developed regions exhibit low WEEE generation but high growth rates, especially in rural areas. This presents new challenges for the central and local governments.

While residential use and discard remain the primary sources of WEEE, commercial use is experiencing rapid growth. Obsolete air conditioners and computers from enterprises already account for 10% and 21% of these two types of waste generation, respectively, with median growth rates of 22% and 20%. The fast growth of WEEE from enterprises can be attributed to the development of manufacturing and tertiary industries, as well as the digitization and informatization of Chinese enterprises in recent years. As China continues to develop, particularly in the high-tech manufacturing and modern service industries, which are information and knowledge-intensive, and as public and private enterprises continue to digitize, the proportion of WEEE generated by enterprises is expected to increase. Therefore, greater attention should be given to the implementation of WEEE collection systems for enterprises.

4.2 Spatial mismatch between WEEE generation and disposal capability

Compared to the spatial distribution of WEEE generation, the distribution of disposal capability is relatively similar and effective. China currently has 109 licensed and certified recycling enterprises spread across 82 cities and 29 provinces. Although this system was initially designed for regional self-sufficiency, the majority of these enterprises are located in the central and eastern regions of China, such as the Yangtze River Delta, Pearl River Delta, Jing-Jin-Ji city cluster, Middle Yangtze River city cluster, Chengyu city cluster, Central Plain city cluster, and the western coast of the Taiwan Strait (Fig. 6(c)). These areas account for over 60% of the total disposal capability (Fig. 6(a)).

However, there is a significant mismatch in the western regions. As illustrated in Fig. 6(d), the disposal capabilities of Xizang, Hainan, Qinghai, Xinjiang, Guangxi, Guizhou, and Gansu are far below their respective generation of WEEE, especially in Xizang and Hainan where there is no disposal capability at all. In 2017, these provinces generated less than 12 million units of WEEE, accounting for only 10% of the total WEEE generation, while their disposal capability was significantly lower at 4.6 million units, representing just 3% of the total capability. This disparity highlights the low levels of WEEE management in these provinces. The western provinces typically have low WEEE generation density and high collection costs due to sparse populations and complex terrains. Consequently, this facilitates the flow of WEEE to unregulated disposal enterprises and hampers the improvement of China's formal recycling rate.

Mismatches also exist at the product level. Obsolete refrigerators and air conditioners constitute approximately 17% and 16% of the total WEEE generation, respectively, while the disposal capabilities for these products only account for 9% and 6%, which is significantly lower than the other three product types (Fig. 6(b)). The low proportion of disposal capability reflects the low formal recycling rate. Over 83% of obsolete refrigerators are informally

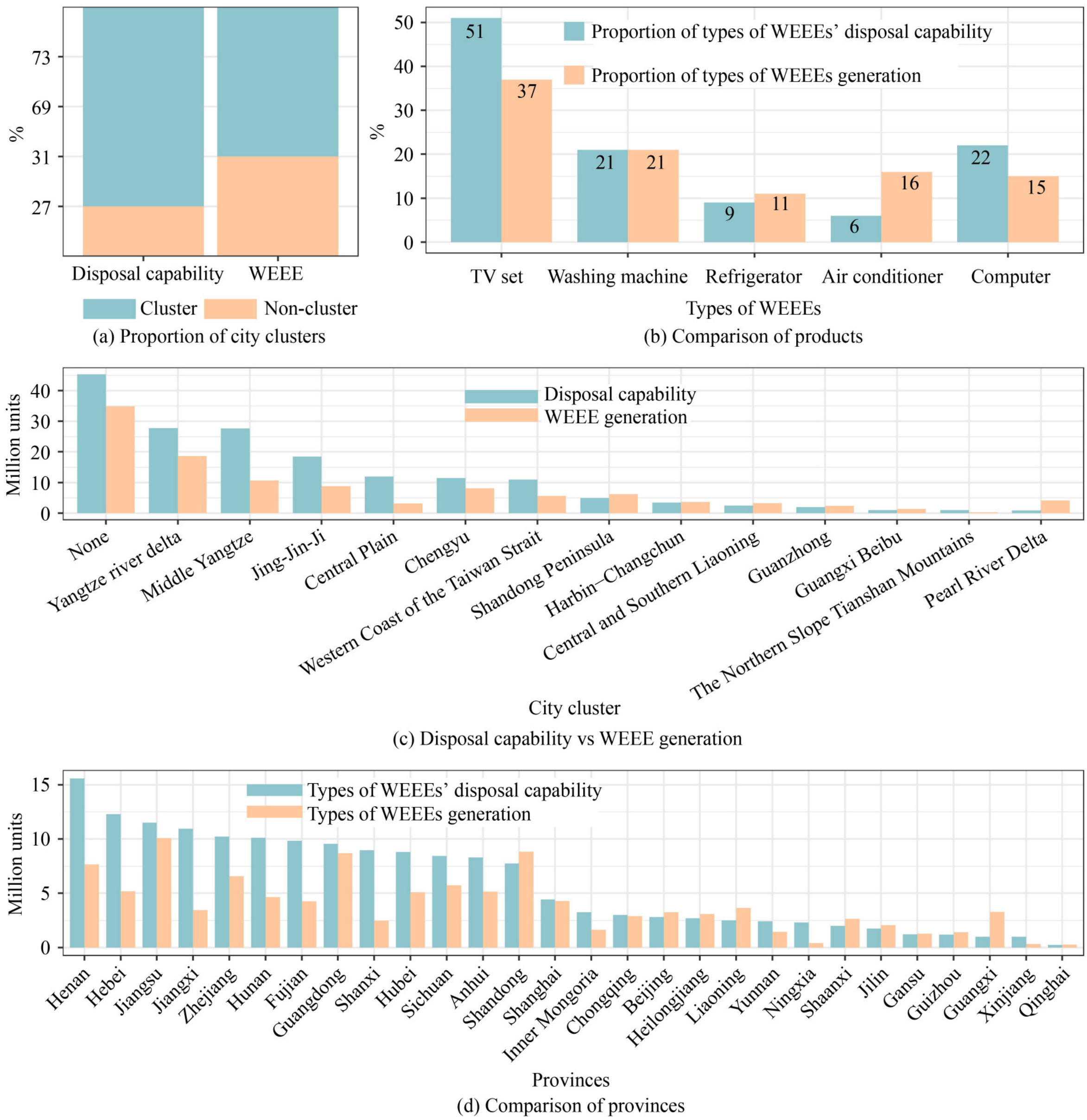


Fig. 6 Comparison of WEEE generation and disposal capability at (a) the national level, (b) product level, (c) city cluster level, (d) provincial level in 2017.

recycled, whereas only 1% of obsolete air conditioners are recycled (Duan et al., 2018). Therefore, the formal collection rate for obsolete refrigerators and air conditioners must be improved, particularly for air conditioners, which are experiencing rapid growth in generation.

4.3 Policy implications

Based on our findings, we have identified four key areas that governments and collection and recycling enterprises should prioritize in order to develop an enhanced management system.

Interregional cooperation is crucial for addressing the mismatch between WEEE generation and disposal capability. Insufficient disposal capability is evident at both the provincial and city levels. Western provinces such as Xizang, Hainan, Qinghai, Xinjiang, Guangxi, Guizhou, and Gansu lack the necessary infrastructure for proper WEEE disposal. Additionally, out of the 109 formal disposal enterprises, they are concentrated in only 82 cities, leaving more than 200 cities without the ability to handle WEEE disposal independently. Consequently, the movement of WEEE between cities and provinces becomes inevitable (Tong et al., 2018; Li et al., 2020b), creating a conflict with China's current territory-based WEEE management system. This poses challenges in regulating the cross-regional transportation of WEEE. Moreover, cities without disposal capability bear the environmental risks associated with improper disposal, unfairly burdening cities that do possess the necessary facilities (Rautela et al., 2021). To address these issues, the establishment of cross-regional collaborative management mechanisms is proposed, particularly for city clusters with high WEEE generation (Tian et al., 2018). Such an approach has proven effective in controlling other types of pollution. (Chen et al., 2020).

Developing areas, particularly less developed cities, need to enhance their disposal capability. These cities face mounting WEEE burdens but are hampered by inadequate infrastructure and high collection costs due to low population density and challenging terrains. Consequently, formal collection rates remain low, resulting in significant resource and environmental losses. Critically, many of these less developed cities are situated in underdeveloped provinces in western China, which include ecological barrier areas and ecologically fragile regions (Ouyang et al., 2016). Without a comprehensive collection and recycling management system in place, unregulated disposal enterprises may be the unintended recipients of WEEE. This poses a direct threat to fragile local ecosystems and compromises the ecological security of the entire country. The central and local governments in these regions must strengthen their WEEE management policies to mitigate these risks

To strengthen the supervision and research on WEEE generated by private enterprises is crucial. The generation of WEEE from both public and private enterprises is rapidly increasing, making it a significant source of WEEE. It is essential for public enterprises to adhere to state-owned asset disposal regulations when dealing with outdated EEE products. Some governments have implemented standards to guide the proper disposal of WEEE into authorized facilities, resulting in notable accomplishments. For instance, in 2019, obsolete air conditioners and computers collected from public enterprises accounted for 8.03% and 7.64%, respectively, of all disposed WEEE (CHEARI, 2020).

However, there is a lack of specific policies targeted at WEEE recycling by private enterprises. Additionally, there is limited data available on the quantity and location of WEEE generated by private enterprises, despite the fact that more than 90% of enterprises are privately owned (Wei et al., 2017). Consequently, there is a pressing need for the development of policies and research in these areas.

It is crucial to optimize China's recycling management system, particularly concerning obsolete refrigerators and air conditioners, as they have the lowest formal recycling rates among the five EEEs. These products contain refrigerants synthesized by chlorofluorocarbons or hydrofluorocarbons, which possess high ozone-depletion potential, contributing significantly to global warming. The low formal recycling rates for these items could potentially result in significant environmental damage (Duan et al., 2018). Thus, it is urgent to enhance the formal recycling rate of obsolete refrigerators and air conditioners, with a particular focus on the latter, given the rapid increase in their generation.

4.4 Uncertainties and limitations

Our findings on WEEE generation align relatively well with previous studies conducted by CHEARI (2020), Forti et al. (2020), and Huang et al. (2020), as depicted in Figure S30 in the supporting information. Most discrepancies fall within the range of five million units. Notably, our figures for the three types of equipment exclusively used by residents (TVs, washing machines, and refrigerators) are marginally higher than previous results. This variation may stem from our use of the most comprehensive stock inventory data available since 1978 when China began widespread usage of household appliances. Consequently, we recommend providing more comprehensive results. Concerning air conditioners and computers, which are used by both residents and enterprises, our figures closely resemble those of CHEARI (2020) but are slightly lower than Huang et al. (2020), who employed a similar lifespan approach to ours. This disparity may be attributed to the challenges in accurately identifying all enterprise EEE stocks. However, the difference for computers is significantly lower compared to air conditioners. One possible explanation is that stock data can include computers acquired through non-standard means such as the gray market (e.g., DIY and smuggling), which are not accounted for in sales data. To achieve a more precise spatiotemporal distribution of WEEE generation in China and establish more accurate WEEE management systems, further research is necessary to examine enterprises' WEEE generation and their recycling behavior. Additionally, it is important to consider varying lifespans for each product in different regions and among users. Solely relying on national data may heighten the uncertainty of the results. Consequently, more studies should be conducted on the lifespan of EEEs in various cities.

5 Conclusions

This research paper presents the construction of the cMAC database and the assessment of WEEE generation in 301 Chinese cities from 1978 to 2017. The study analyzes three sources of WEEE generation in each city: (1) urban residents, (2) rural residents, and (3) enterprises. The findings indicate that WEEE generation, both at the national and city levels, steadily increased albeit at lower growth rates, without reaching its peak. The majority of WEEE was generated in city clusters with advanced economic development in eastern and central China, which also exhibited the highest disposal capability. In contrast, western cities accounted for only 10% of the total WEEE generation, with an even lower disposal capability of merely 3%. Consequently, these cities face an escalating issue of insufficient disposal capacity due to the accelerated generation of WEEE. Urban areas experience high WEEE generation but have a low growth rate, while rural areas and enterprises present the opposite trend. Therefore, there is a need to enhance the collection and recycling capability of WEEE originating from western cities, rural areas, and enterprises. The study reveals that obsolete TV sets, washing machines, and refrigerators in certain cities have either reached or are nearing their peak points, whereas outdated air conditioners and computers across all cities continue to display growth trends and contribute significantly to the overall WEEE generation. Compared to their disposal capabilities, obsolete refrigerators and air conditioners exhibit the highest environmental impact and the lowest recycling rates among these five products. Thus, particular attention needs to be given to these two products. In summary, disparities exist between WEEE generation and disposal capability in terms of spatial distribution and product types. To enhance the recycling system, it is crucial to strengthen cross-city collaboration and identify key areas, sources, and products that require improvement.

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