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Using weighted entropy to measure the recyclability of municipal solid waste in China: Exploring the geographical disparity for circular economy

Xin Tong *, Haofan Yu, Tao Liu

College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China

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ABSTRACT

Solid waste recycling in developing countries has been largely relying on the informal recycling sector which intelligently uses the tacit knowledge within the hierarchical network of labor division to capture the value from the geographically uneven distribution of waste generation and demands on secondary materials. Previous studies on solid waste recycling mainly have a material-centric view on economic value. In this paper, an entropy-weighted recyclability index (EWRI) is developed to quantify the recyclability of Municipal Solid Waste (MSW) in China at the prefectural city level by integrating the road transportation density and regional recycling capability into the categories of waste physical components regarding the cost to deliver the waste from generating sources to the conversion sites for recycling. The result confirms the existence of an east-west gradient regional disparity in recyclability of Municipal Solid Waste (MSW) among cities for the recyclable components. The 339 prefectural cities were classified into 4 grades, namely “best, good, normal, and difficult” for the recyclability of local MSW with guidelines for planning of regional recycling infrastructure, respectively. In conclusion, general guidelines for the building of wise-waste city infrastructure to fit the local context in developing countries is advised.

1. Introduction

The management of Municipal Solid Waste (MSW) is one of the pillars of the circular economy by extending and closing the material cycles that accounts for waste input-output in economic flows (Tsai et al., 2020). Worldwide efforts are needed to raise awareness of various stakeholders to act wisely in response to the urban waste issues at the national, regional, and city levels (UN Habitat, 2018). Various features of urbanization have been identified with significant impacts on the generation and composition of MSW (Chen, 2018; Huang et al., 2020b; Zhang et al., 2019), which requires smart infrastructure planning for a zero-waste strategy (Gu et al., 2021; Marques et al., 2019). Considering the high reliance on informal sector for recycling in most developing countries (Wilson et al., 2006), the transition of the MSW management in these countries has to address not only the resource and environmental impacts, but also social and economic issues (Ezeah et al., 2013).

China, the most populous country with fast economic growth and dramatic social transition in the last four decades, has witnessed the MSW generation nearly doubled in less than 20 years (NBS, 2000–2019), accompanying with a spatially uneven transition of MSW management due to the large regional disparity (Duan et al., 2020; Zhang et al., 2010). To avoid the growing environmental burdens caused by illegal dumping, China has established regulations and policies for MSW for cities with reference to the experiences of developed countries, such as Japan and Germany (Abdel-Shafy and Mansour, 2018). Increased investment has been devoted to the building of modern waste disposal facilities, like incineration and sanitary landfill since the 1990s (Ding et al., 2021; Yang et al., 2019). In 2018, the MSW ended in landfill and incineration jointly reached 96% of the total municipal collected and transported solid waste in cities in China, in which the share of landfill decreased from the highest 62% in 2012 to 51% in 2018, while that of incineration increased to 45% from near 0 within a decade (NBS, 2000–2019).

In parallel with the development of capital-intensive formal urban waste management system, most cities have been long relying on the urban informal recyclers to collect and sort the household solid waste (Steuer et al., 2017; Xiao et al., 2018). Therefore, compared to developed countries, the MSW in cities of China used to have a very low fraction of valuable recyclables, but a high fraction of organic food waste (Zhen-shan et al., 2009). However, with increasing labor cost and

* Corresponding author.
E-mail addresses: Tongxin@urban.pku.edu.cn (X. Tong), yuhaofan@pku.edu.cn (H. Yu), liutao@pku.edu.cn (T. Liu).

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ever strict environmental standards, the informal recycling system is struggling for survival (Steuer et al., 2018). Even with a more efficient and flexible trade network to transport the recyclables from consumers to the production areas (Steuer et al., 2017), the informal recycling system has generally melted down with the stagnant secondary material market as macro-economic growth flattening in recent years. The transition of the informal recycling system calls for a reform of the urban waste management system to integrate the flows of recyclables at the very source of waste generation.

In order to encourage the waste reduction at source and promote recycling, various efforts have been devoted at city level. By extending the circular economic system for production built during the period of fast economic growth, China launched the work plan for the "zero-waste city" pilot program in 2018 to reform the recycling infrastructure in order to minimize waste generation from the lifecycle perspective as well as to reduce the local burden of landfills and incineration (GOSC, 2018). As to the consumer side, the dry mixed recyclable waste has been required to be collected separately from residential communities. And the national target for the recycling rate of MSW has been set to surpass 35% before 2025 (MHUD, 2020).

In average, the recyclables account for 30–40% in MSW generation in China and keep growing along the economic growth (Wei et al., 2018; Niu et al., 2021). Local factors could have impacts on the generation of MSW, such as the changing lifestyle and industrial structure (Gu et al., 2014; Wei et al., 2018). Therefore, significant spatiotemporal varieties exist in the physical components of recyclable waste generated in different regions (Abdel-Shafy and Mansour, 2018; Wang, K. et al., 2020; Wei et al., 2018). The recycling potential of recyclable waste has been studied in-depth for representative cities based on field studies (Duan et al., 2020; Gu et al., 2018) to support the planning of infrastructure for recycling. However, gaps exist between the national policy and the local actions.

Although the four-stream waste separation, namely, food waste, recyclable waste, toxic waste, and the residues, has been standardized for the planning of recycling infrastructure for MSW in cities (Lv et al., 2020), the recyclables can hardly rely on the local infrastructure like incinerator or landfill sites, but an efficient logistic system connecting to a regional production network in the market system (Gu et al., 2021). Existing studies mainly took a material-centric view in the analysis of waste recyclability (Gu et al., 2021; Ma et al., 2020). However, to make material recycling practicable, transportation condition and regional recycling capacity are key factors.

The aim of this paper is to evaluate the recyclability of MSW at city level for optimization of regional recycling infrastructure with the background of a structural change of the recycling sector in China. The next section explains the material and methods we used in the analysis. An Entropy-Weighted Recyclability Index (EWRI) that integrated the geographical factors, namely, transportation accessibility and regional recycling capacity, into the volume and composition of waste generation is developed to (1) illustrate the spatial pattern of the regional diversity of MSW recyclability in China; and (2) quantify the differentiation of recyclability of MSW in China at city level. Section 3 presents the result of EWRI model for 2018 and discusses its implications for the design of regional recycling infrastructure. In concluding remarks, general guidelines for the development of circular economy in developing countries are addressed.

2. Material and methods

As a supplement to other evaluation tools, such as Material Flow Analysis (MFA), the concept of entropy, which comes from the information theory to evaluate the average level of "information" in a random variable inherent in its possible outcomes, has been proved useful in the construction of indicators for circularity evaluation on the complex system (Laner et al., 2017). Existing studies in waste management mainly use the concept of entropy in the evaluation of material recyclability, from specific waste flow (Yue et al., 2009; Zeng and Li, 2016) to the different stages of a product's lifecycle (Parchomenko et al., 2020; Rechberger and Graedel, 2002). In decision-making analysis, entropy is used in the weighting method by measuring the value dispersion among many randomly distributed variables that could have impacts on the decision goals. The greater the degree of dispersion of a variable means the greater the degree of differentiation, therefore more information can be derived from the attribute represented by this variable. This concept can help us to identify the factors with significant spatial differences that contribute to differentiate the recyclability of MSW in each city. The factors analyzed in this research include three dimensions of the recyclables supply: material, transportation, and recycling capacity. The economic value of secondary materials is a very important factor for recycling in practice, however, the price fluctuation is generally transparent, for which the spatial difference is mainly induced by the transportation and recycling capacity. Therefore, the market price of the secondary materials would be excluded from the index.

2.1. Data

2.1.1. Generation and composition of MSW

The generation and composition are most important in assessing the recyclability of the MSW (Karak et al., 2012). Detailed meta-analysis on the spatiotemporal characteristic on the generation and composition of MSW has been conducted for the 7 major regions in China, namely North China, East China, Northeast China, Northwest China, Central China, South China, and Southwest China based on the comprehensive literature review on waste components analysis from field observation (Ma et al., 2020; Wei et al., 2018). Based on the research result of Wei et al. (2018), the volume of MSW generated by each city in China in 2018 was estimated from the provincial transported urban solid waste volume weighted by city population (see Fig. 1). The data of city population were derived from the *China City Statistical Yearbook 2018* and supplemented and verified by those published in provincial statistical yearbooks. With the fraction of physical components of MSW in the 7 major regions (see Table 1), the quantity of each component of MSW in cities was calculated (See supplementary 1). Six of the nine categories are recyclable waste, including paper, plastics and rubber, textile, wood, metal, and glass.[1] In general, the recyclables account for 30% of MSW for the whole country, while the highest reaches 38% in North China and the lowest 22% in Central China.

2.1.2. Regional recycling capacity

As the factory of the world, China has become one of the most important destinations of recyclable goods in the world due to the huge demands on industrial materials for manufacturing, which make the recycling more economically efficient than other places (Hu et al., 2020; Huang et al., 2020a). The spatial distribution of industries generally shaped the recycling capacity for valuable recyclable goods under the market mechanism. Fig. 2 shows the spatial distribution of recycling enterprises for metal and nonmetal materials in 2018, respectively (NSB database, 2019). These enterprises are the large ones in the recycling sector with annual industrial output above RMB ¥ 20 million (around US $309 thousand). Although a large number of small workshops were not included in the formal statistical databases, there are two reasons that can justify the use of the spatial distribution of the large recycling enterprises as the indicator for the regional recycling capacity. First, the

[1] Food waste and ash and stones are not included in calculation. Because, although food waste can be recycled through composting for nutrients and energy recovery, and ash and stones could be used in construction materials; these two kinds of recycling generally require specific treatment facilities, which have been already included in the planning of local waste disposal infrastructure.

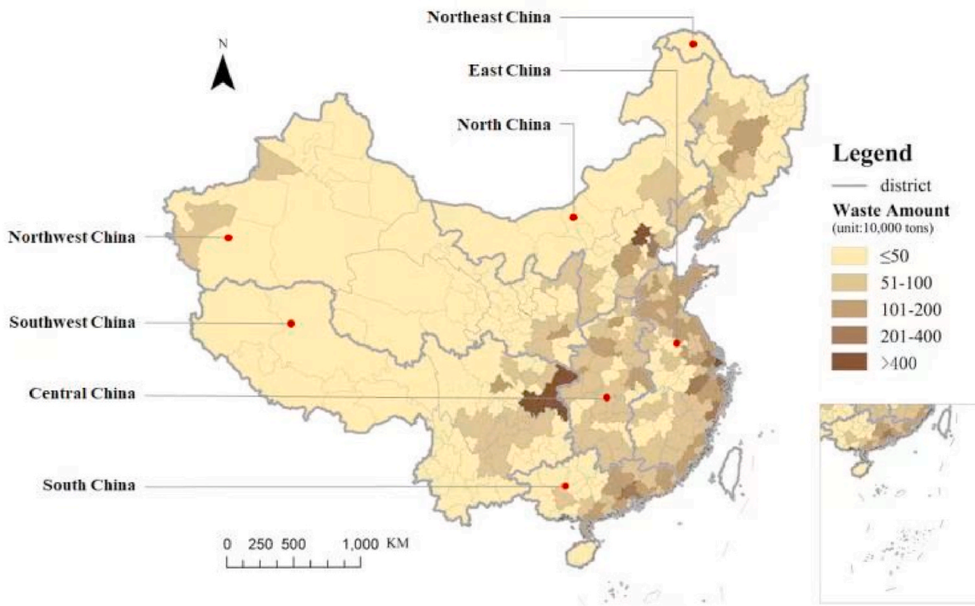

Fig. 1. The estimated generation of MSW in each city in China in 2018.

Table 1
Estimated MSW component fractions in different regions in China.

Regions	Recyclable waste						Food	Ash and stone	others
	Paper	Plastics and rubber	Textile	Wood	Metal	Glass			
East China	8.65	12.45	2.30	1.77	0.65	2.92	64.50	6.27	2.02
South China	11.81	13.49	3.71	2.03	0.74	1.86	51.18	11.64	5.85
Southwest China	9.98	12.61	2.81	2.50	1.16	1.62	52.22	13.32	7.11
Northwest China	6.85	9.41	2.72	1.75	1.21	2.89	51.93	27.22	4.25
North China	11.57	11.77	4.18	4.29	2.75	3.92	50.76	10.79	0.92
Northeast China	7.24	11.14	2.69	5.94	1.08	3.00	58.87	7.33	6.31
Central China	3.12	8.61	4.04	4.75	0.76	0.81	49.42	26.39	8.30
Whole country	8.94	11.54	2.86	2.74	1.15	2.60	56.79	11.58	4.31

Source: Adapted from Wei et al. (2018).

market competition in the recycling market has reinforced the locational advantage of several industrial clusters where the small workshops has higher probability to grow into large enterprises. Second, but more importantly, the recycling sector is under dramatic restructuring in recent years in China. The market condition generally prefers large companies to small workshops. There used to be a large number of small recycling workshops near big cities, for example, the rural villages in Hebei surrounding Beijing. However, as the local environmental regulations getting strict, most of these small clusters of informal workshops have been shut down. The companies with technical and investment capability can move to the circular economy industrial parks, and expand their processing capacity to reach the target of the economy of scale.

2.1.3. *The transportation system linking waste to resources*

Transportation is crucial for waste recycling, especially in the tradeoff between recycling and other disposal options (Merrild et al., 2012). Different physical components of the waste have different sensitivity to the transportation cost. For heavy and low-value recyclables, such as glass and wood, the cost of transportation restrains the possibility for long-distance recycling. Lacking local recycling capacity could lead the waste flows into landfill or incineration. For the large amount of recyclable goods with high value and easy for transportation, such as paper, plastics and metals, well sorted waste can be traded in long distance and large volume to achieve a high recycling rate. Either disposed locally or recycled in distance, road transportation is the major approach for the convey of recyclable goods in China.

We use road density as an indicator for the transportation accessibility of recyclable goods. The road density is a simple indicator of the road network structure, which is measured by the total length of the regional road network divided by the area of the region. Given the network topology is similar in different regions, higher road density implies higher availability of short alternative routes, thus better transportation accessibility (Jenelius, 2009; Wang, S. et al., 2020). Road density is easier to calculate and to acquire data compared to more sophisticated methods for accessibility calculation. In addition, for road freight transport, the road density is more important than the quality (Wessel, 2019), especially that require adequate roads for the "first-mile" and "last-mile" logistics (Wygonik and Goodchild, 2018), which is particularly important for the collection of recyclable waste. Based on our qualitative field studies on recycling sectors in different regions in China, two levels of regional road density were used as rough indicators for transportation conditions of different categories of the recyclable waste: (1) city level road density for glass and wood, which can be recycled in short distance, and the collection from the consumer side is more influential in the logistic cost (See Fig. 3); and (2) regional level road density for paper, plastics, metal, and textile, which can usually be collected and recycled in long distance. The road density was calculated from the national road dataset from the Geographic Data Sharing Infrastructure of Peking University (2018) (See Table 2).

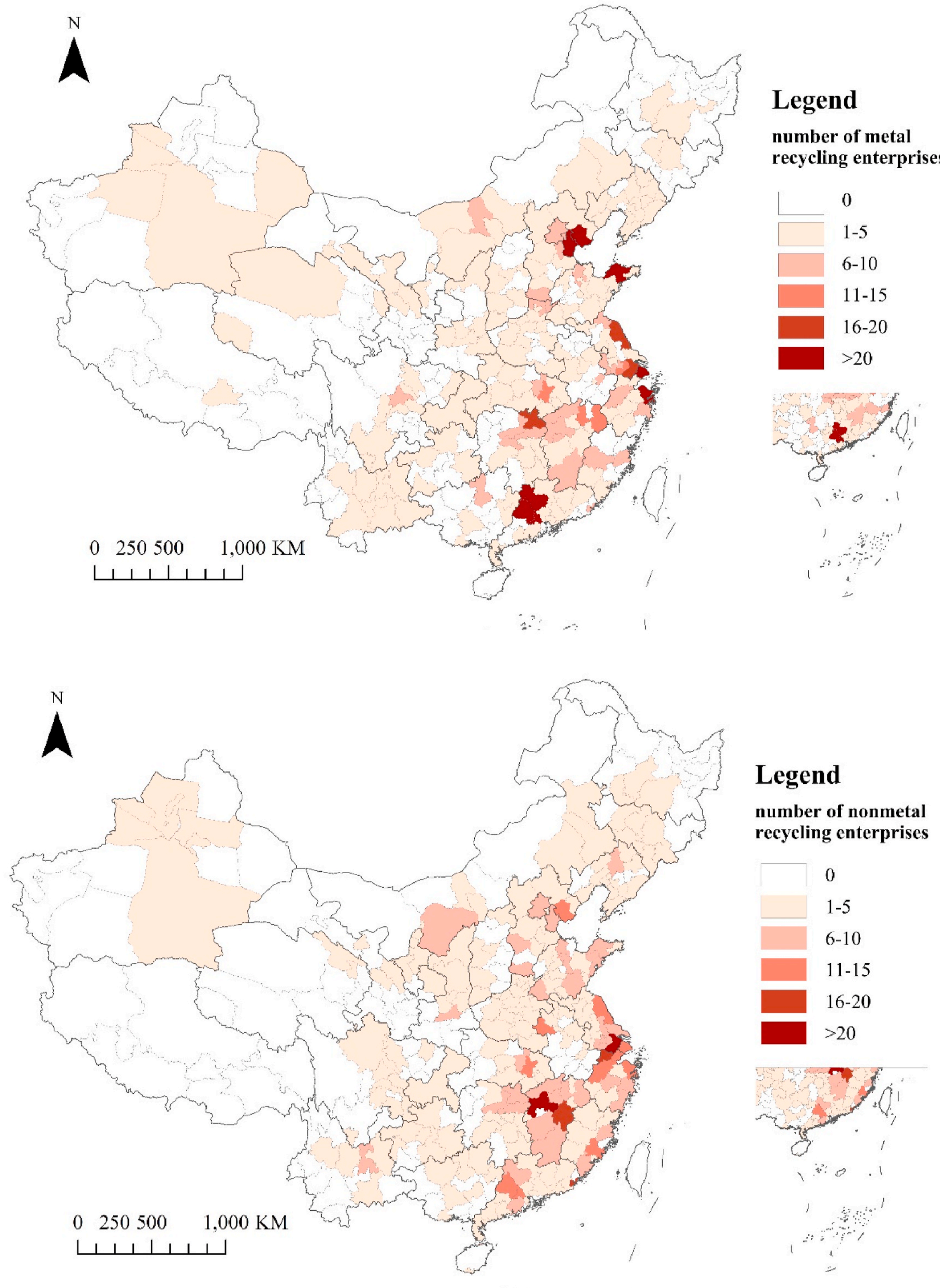

Fig. 2. The spatial distribution of recycling enterprises in China in 2018.
Source: NBS database, 2019.

2.2. Entropy-weighted recyclability index (EWRI)

The Entropy-Weighted Recyclability Index (EWRI) was built to integrate the physical components data of recyclable waste in MSW with regional transportation and recycling capacity information into a representative value that reflects the relative potential for recycling for each city. The algorithm to compute the EWRI follows the Shannon-entropy (Shannon, 1948), measuring the variance of a probability distribution for the 6 categories of recyclable components in MSW in the 339 prefecture-level cities of China. The EWRI is calculated as following:

First, the information entropy (e_j) is defined as Eq (1):

$$e_j = -\frac{1}{log_2(n)}\sum_{i=1}^{n} P_{ij} log_2(P_{ij}) \tag{1}$$

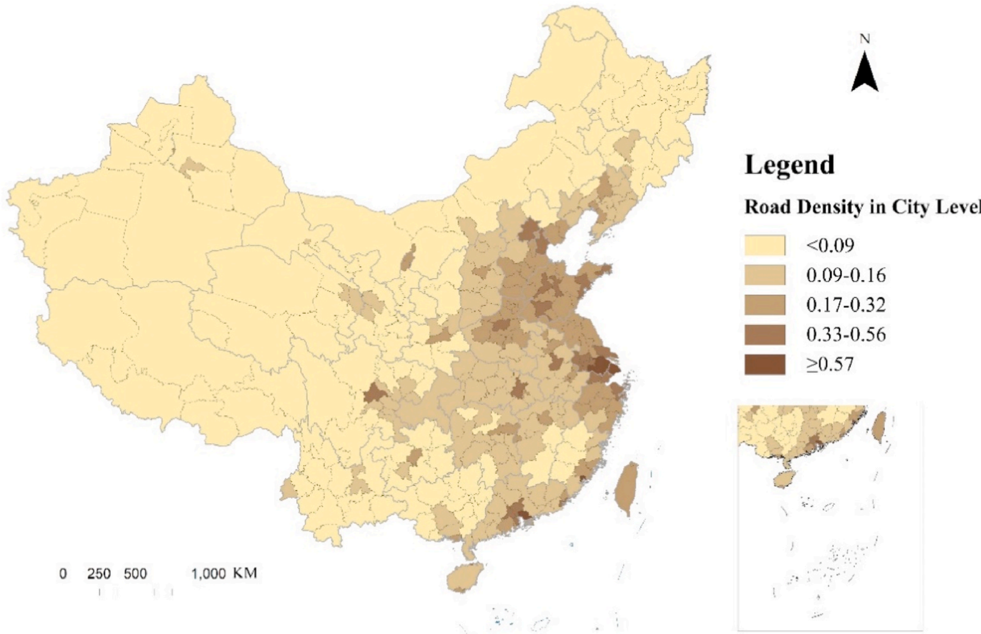

Fig. 3. The road density at city level in China in 2018.

Table 2
Regional road density and number of recycling enterprises in China.

Regions	Road density km/km^2	Number of recycling enterprises	
		metals	Non-metals
East China	**0.19**	**320**	**407**
South China	**0.11**	**135**	**114**
Southwest China	**0.04**	**40**	**46**
Northwest China	**0.02**	**33**	**54**
North China	**0.06**	**137**	**88**
Northeast China	**0.05**	**33**	**44**
Central China	**0.12**	**140**	**116**

Where n is the total number of cities and P_{ij} is the normalized value of the recyclability index q_{ij} which is expressed as Eq (2):

$$P_{ij} = \frac{q_{ij} + A}{\sum_{i=1}^{n}(q_{ij} + A)} \tag{2}$$

We introduced a small offset value A to avoid $log_2(0)$. The recyclability rating scale (q_{ij}) for physical component j in city i was calculated regarding the local factors of transportation and recycling capacity as Eq (3):

$$q_{ij} = C_{ij} \times R_{ij} \times T_{ij} \tag{3}$$

Where: C_{ij} is the estimated quantity of physical component j in city i (as shown in Fig. 1); R_{ij} is the regional recycling capacity: for short distance recycling waste as glass and wood, R_{ij} is the non-metal recycling enterprises density of the province; for long-distance recycling waste as paper, plastics, textile, R_{ij} is the non-metal recycling enterprises density of the region; and for metals, R_{ij} is the metal recycling enterprises density of the region (as shown in Fig. 2 and Table 2). T_{ij} is the transportation factor: for local recycling waste as glass and wood, T_{ij} is the road density of the city (as shown in Fig. 3); for long-distance recycling waste as paper, plastics, textile and metals, T_{ij} is the road density of the region that city i lies in (as shown in Table 2).

Then, the entropy weight of each parameter was calculated as Eq (4):

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{z}(1 - e_j)} \tag{4}$$

Where z is the total number of parameters (j = 1, 2, 3 … z).

Finally, the Entropy Weighted Recyclability Index (EWRI) is calculated as Eq (5):

$$EWRI = \sum_{j=1}^{n} w_j \times q_j \tag{5}$$

3. Results and discussion

3.1. The regional disparity of recyclability for MSW

All cities in China were divided into 4 levels according to the relative recyclability of their MSW calculated by the Entropy Weighted Recyclability Index (EWRI) in 2018 (Fig. 4). Compared with Fig. 1, the spatial disparity in the volume of MSW generation, this result highlights the impacts of regional recycling compacity and road transportation accessibility. There is a clear pattern of the east-west gradient of recyclability, in which cities with the highest scores are concentrated in the eastern coastal regions, those with modest scores are located in the central area, while the cities in the western hinterland generally facing difficulty to recycle their MSW due to lack of recycling capacity and low transportation accessibility. This result generally confirms the existing intuitive judgment within the sector on the broad interregional disparity between east and west (Gu et al., 2021), but more detailed intra-regional differences can be illustrated.

3.2. The recycling system in transition

The MSW management developed quickly in China in the last decades. The improvement of waste disposal facilities has greatly enhanced the health and environmental performance of urban waste management. However, as most existing literature has already pointed out, lacking garbage sorting at source and mixed waste collection hindered the effective recycling of the recyclable components in MSW, which increased quickly due to the changing lifestyle (Gu et al., 2018; Zhen-shan et al., 2009).

The traditional informal recycling sector generally depended on small peddlers collecting the valuable recyclables door-to-door, and urban scavengers sorting out the low-value recyclables from dustbins or

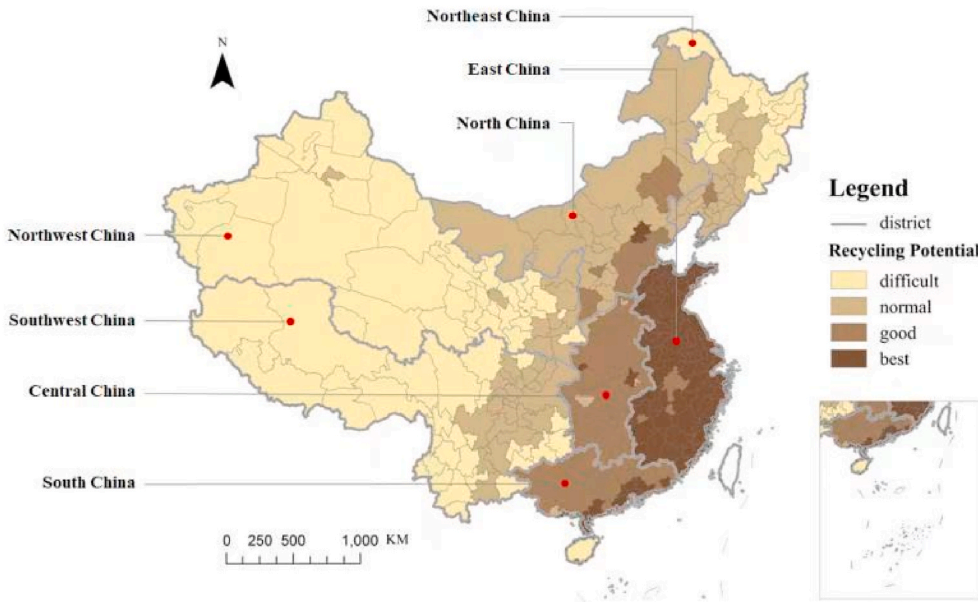

Fig. 4. The recyclability of MSW in cities of China.

landfill sites. This collection system was linked to a vast number of family-based small workshops that are generally located in the city periphery not far away from the urban centers. The transportation accessibility and recycling potential were intuitively contained within the trading network of the informal recycling sector to squeeze the value of secondary material from the waste. Without structural change of this traditional recycling system, the informal recycling sector will continue to be segregated from the general economic development in two directions: on the consumer side, the recycling cost increases with the labor cost which leads to more and more recyclable components in the MSW economically infeasible for recycling; while on the demand side of the secondary materials, the recycling plants to converse waste into resources have to chase for low-cost locations in peripheral areas farther away from the consumption centers, thus requiring higher level of economy of scale to support the additional transportation cost. This structural change of informal recycling system was geographical uneven due to the spatial dynamic of the production organization.

A new movement of waste sorting initiatives has been mobilized in Chinese cities in recent years. This movement is a sign of the structural change of the total recycling sector. Experiences in developed countries have shown that the involvement of the consumers in garbage sorting could effectively divert the recyclable waste flows away from the disposal destination like incineration and landfill. The well-sorted recyclable waste could afford even cross-continental transportation for recycling when the demand side of secondary materials exists. However, without an integration strategy towards regional circular economy, the recycling sector could still be exiled to distant backward areas and evolve downwards in a race-to-bottom way.

Fig. 4 demonstrates a possible spatial strategy for building the regional close-loop network. The east coastal industrialized regions with higher recyclability of MSW have the advantage for the development of the recycling industry. These regions also have the capability to invest in new infrastructure for circular economy. With a regional policy to support the zero-waste city initiatives, further division of labor in the recycling value chain could strengthen the locational advantage of existing clusters, and their linkages with the regional manufacturing base. For example, the emerging business models for post-consumer recycling transformed from the traditional informal recycling enterprises, like Huge in Zhejiang and Aifenlei in Beijing, provide all-inclusive recyclables collection in the residential communities to gain economy of scale for downstream sorting and recycling. More stable business linkages are established between these companies and large downstream recycling plants.

3.3. The implications for optimization of the recycling system

With the background of the structural change of the recycling sector in China, the EWRI evaluation result can provide some implications for the optimization of regional recycling infrastructure regarding the local context for MSW recyclability.

3.3.1. Optimization of the regional recycling capacity

Recycling enterprises play the pivot role in the conversion of waste into resources. As the overall environment and labor protection standards increase in China, the recycling enterprises that can survive in market competition have accumulated both technical and managerial capability. The efforts of the local government to build circular economy industrial parks provide not only the space for these companies, but create and facilitate cooperation and networking among the recycling enterprises as well as their customers. However, at the city-level, the experiences of building circular economy industrial parks by the municipal government that prevalent in the east coastal areas may not be feasible for the western hinterland. The recycling activities have been deeply intertwined with the production network in the division of labor. Inter-regional cooperation is needed to enhance the efficiency in the operation of the regional recycling facilities.

The recycling capacity indicator in this research only covers the recycling enterprises with annual industrial output above RMB￥20 million (=USD $3 million), as the criteria of the inclusion into database of the national bureau statistics. There are much more small firms for local recycling businesses. More detailed data work is needed to construct a comprehensive database for the recycling capacity based on the material and product categories, for which the entropy analysis can be used at multiple levels and from the perspective of different stakeholders.

3.3.2. Involving informal sector with information technology

As the crucial factor for recyclability, the physical transportation condition can change little in future, but the information technology has great potential for improving the efficiency of transportation (Gu et al., 2021). Various new business models are emerging in China to integrate the informal recycling sector into the formal urban waste management system (Wei et al., 2021), as well as the development of regional circular economic system at large (Tong et al., 2018). The weakness of informal recycling lies in the poor environmental protection and lack of economy of scale for small workshops when handling environmental hazardous materials. However, there is significant strength for the informal network for collection, in which the information to match the supply and demand in the recycling value chains can be used wisely to improve the value of the recyclable waste.

The EWRI model presented in this research illustrates the possibility to quantify the fuzzy pattern of regional disparity in recyclability by using the concept of entropy to highlight the factors with high regional differentiations. This is the way to simulate the informal networks to respond to the market dynamics and heterogeneity through tacit knowledge.

3.3.3. Regional differentiated policies for recycling infrastructure planning

Under the background of the structural change of recycling sector in China, differentiated policy implications for regions with various recyclability of MSW can be generated from the result of the EWRI presented above.

Firstly, for cities in the eastern coastal regions with high recyclability of MSW, an integrated recycling infrastructure that fully cover the whole product lifecycle should be built at the regional level to support the transition of regional production network towards circular economy. By introducing the Extended Producer Responsibility, market incentives are provided to enhance the efficiency for recycling, as well as encourage technological innovation and new business model for post-consumer recycling.

Secondly, for cities in the central regions with modest recyclability, the generation of MSW has been projected with quick growth in coming years as the result of large population and fast economic development. There has been a trend of location shift of manufacturing from eastern coastal regions to the central regions as the domestic demands increasingly replace the overseas demands for industrial development, which leads to environmental pressures for hinterland regions (Zhou et al., 2017; He et al., 2018; Huang et al., 2020). However, the development of recycling sector, which is still dominated by the informal sectors, is left behind the general economic development in these regions. Therefore, besides the waste sorting and collection at source, regional recycling capacity should be improved to fit for the overall development of production and consumption. In future, the general disparities between the east and central regions could gradually reduce. An integrated market for the recyclables is emerging among these populated regions to facilitate further labor division among various cities.

Thirdly, for cities in the western hinterland regions with low recyclability of MSW, the efforts to better sort the waste at source could be probably hindered by the high transportation cost and low regional recycling capacity. For the long-distance recycling materials, like paper, plastics, and metals, improving the source separation and regional reverse logistic system could offset the disadvantage to some extent. However, the increase of waste generation could generally result in the over burden of local landfills. More fundamental policies are needed to encourage the technological choices for materials that could be easily disposal locally.

4. Conclusions: towards an inclusive circular economy for wise-waste cities

This paper presents a new method to evaluate the recyclability of MSW as a tool for infrastructure optimization in current zero-waste city initiatives in China. The result generally confirms the existence of an east-west gradient for the recyclability of MSW for cities in China. The added value of the weighted entropy method presented in this article is that, apart from the differences of material components, the regional transportation and recycling capacity also play critical roles in the regional disparity of recyclability of MSW. This result highlights the importance of differentiated policies and planning strategy in the transition of the regional production system towards circular economy. In order to divert more recyclable waste from disposal to recycling, transportation between the waste generation and the recycling sites is crucial to integrate the recycling sector into the regional production network. However, the information of waste flows is generally fuzzy and dynamic, making the standardized planning of recycling infrastructure infeasible in regions with low transportation accessibility and recycling capacity. In addition, without policy interventions, the recycling activities within the informal sectors can hardly be sustainable under both pressure from labor cost and environmental standards in the regions with location advantages of transportation and industrial base.

This research uses the concept of entropy to embody the tacit knowledge within the informal recycling network that intelligently deals with fuzzy information in the complex waste flows across regions. By presenting the geographical unevenness of recyclability of MSW, we call for the construction of regional circular economic system that empowers the diligent individuals working in different stages of the recycling value chains, and create new opportunities for wealth creation and prosperity from the circular economy.

CRediT authorship contribution statement

Xin Tong: Conceptualization, Methodology, Writing – original draft. **Haofan Yu:** Data curation, Visualization, Investigation. **Tao Liu:** Data curation, Validation, Writing – review & editing.

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.

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