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Comparative assessment of circular economy development in China's four megacities: The case of Beijing, Chongqing, Shanghai and Urumqi

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A B S T R A C T

Resources scarcity and environmental pollution in China negatively influence the country's sustainable development. Circular Economy (CE), which established on the basis of "3R principals", was adopted by the Chinese authorities as a national development strategy to reduce resource consumption and mitigate environmental pollution. After more than ten years' implementation of CE strategy, it is of vital importance to investigate the progresses and current status of CE development in China, especially in those China's megacities from both spatial and temporal perspectives, so as to identify the barriers of local CE development in megacities. To achieve such an objective, this study assesses the CE development in China's four megacities during the last ten years by using one unified indicator system. Results indicate that significant disparities exist among China's four megacities regarding both CE development index trajectory and CE internal structure. While all four megacities had significantly improved their CE development since 2005, megacities located in eastern China, namely Beijing and Shanghai, had better CE development performances than megacities from western China, namely Urumqi and Chongqing. With respect to the composition of CE development index, Beijing and Urumqi were doing better on balancing the development of CE's four aspects, namely, resource consumption intensity (RCI), waste emission intensity (WEI), waste recycling and utilization rate (WRUR) and waste disposal level (WDL). In contrast, CE development in Chongqing and Shanghai was primarily attributed to the three aspects of RCI, WEI and WDL, and the WRUR aspects had contributed little to their CE development during the last ten years, indicating an unbalanced CE development status. Additional, Shanghai and Chongqing increased faster on annual average CE development index, and the growth of CE development index of Urumqi was the slowest among the four megacities. In order to promote the CE development performance in China's four megacities, several measures have been proposed, including providing financial and technological support to Urumqi and Chongqing, promoting the recycling of reclaimed wastewater in Chongqing and Shanghai, supporting the application of integrated waste management, as well as encouraging the participation of local residents. This study could provide valuable reference for countries and regions that adopt CE as their development mode.

1. Introduction

Circular economy (CE) emphasizes the conversion from traditional linear economic system to a circular economic system by considering the relationship between resource use and waste residuals (Pearce and Turner, 1990; Su et al., 2013). It becomes more

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popular to the academic society, especially in Germany, Japan and China (Geng and Doberstein, 2008; Geng et al., 2010). Through the realization of a closed loop of materials flow in the entire economic system (Geng and Doberstein, 2008), CE aims to achieve environmental protection, pollution prevention and sustainable development simultaneously by conversion, reuse and recycle of resources (Bilitewski, 2008). Germany is often entitled as a forerunner of CE due to the enactment of its “Closed Substance Cycle and Waste Management Act” in 1996 (Heck, 2006). This law provides a closed cycle waste management and ensured environmentally compatible waste disposal (Su et al., 2013). In addition, in order to promote the creation of a recycling-oriented society, Japanese government established a comprehensive legislative system, incorporating a series of laws and regulations that related to waste management and recycling. Such a legislative system was built based upon the Basic Law for the Promotion of the Creation of a Recycling-Oriented Society, which put into force in January 2001 (METI, 2004; Morioka et al., 2005). It provides quantitative targets for recycling and dematerialization of Japanese society (Van Berkel et al., 2009).

Inspired by those waste management and recycling initiatives from German and Japanese authorities, Chinese government created its own CE development pattern. In China, the original concept of CE has been extended from narrow waste recycling to broad efficiency-oriented control during the closed-loop flows of materials at all stages of production, distribution and consumption (Su et al., 2013). In other words, rather than an environmental management policy, CE has been chosen as one development strategy to help China move toward a more sustainable economic structure (Geng and Doberstein, 2008). National Development and Reform Commission of China (NDRC) is the leading authority to promote CE in China. Two batches of circular economy pilot projects were released by NDRC in 2005 and 2007, respectively (Geng et al., 2012; Xue et al., 2010). In total, those CE pilot projects covered the participation of 178 pilot entities, including 105 enterprises, 37 industrial parks and 36 industrial regions.[1] In addition, another CE pilot project was released by NDRC in 2015, focusing on CE implementation at the city level (including 25 cities and 26 counties). Apart from the initiation of national pilot projects, China's first CE law, named *Circular Economy Promotion Law of the People's Republic of China*, was formally enacted in January 1, 2009. This law requires that national, provincial and municipal governmental agencies should prepare their own CE development plan, including objectives, scopes, main contents, key tasks and management measures, as well as providing target values for several specific indicators such as resource productivity, waste reuse and recycling rates, and etc.

To date, CE policies have been implemented in China for more than ten years. It is of vital importance to investigate the progress of CE implementation, especially, to uncover the key barriers so that valuable policy insights can be obtained for effective policy instruments development. Under such a circumstance, it is critical to conduct a scientific analysis on CE performance by developing proper indicators. Practically, a comprehensive evaluation of national CE development conducted by China's National Bureau of Statistics (CNBS) in 2015 shows that CE development in China achieved remarkable success since 2005 and the CE development index reached 137.6 in 2013 (National Bureau of Statistics of China, 2015). Academically, Wu et al. (2014) evaluated the CE efficiency of 30 Chinese regions for the period of 2005–2010 by employing super-efficiency DEA window analysis. Liu et al. (2016) evaluated the overall benefits of industrial symbiosis in Shenyang economic development area by employing a hybrid method of emergy analysis and index decomposition analysis. Guo et al. (2016) evaluated the economic and environmental benefits of CE implementation both at the industrial units and the entire industrial clusters levels in western China. Most of these studies focus on the assessment of CE development either in a single area during a certain period or among various areas for a specific year, but with less attentions on the comparison of CE development among different regions over time. Under such a circumstance, this study fills such a gap by employing a comparative approach in China's four megacities, namely, Beijing, Chongqing, Shanghai, Urumqi for the period of 2005–2014. Especially, the differences of four megacities' CE development patterns were explored, and the key barriers of each megacity's CE development were identified. After this introduction section, section 2 presents the methods, including introduction of research areas, establishment of indicator system and the accounting methods. Section 3 presents key research findings and section 4 discusses policy implications. Section 5 draws research conclusions of this study.

2. Methods and data

2.1. Introduction of research areas

In order to investigate and compare the CE development in China's different regions, four megacities including Beijing, Chongqing, Shanghai and Urumqi, located in different regions of China, were selected in this study, as presented in Fig. 1. Beijing, Chongqing and Shanghai are three municipal cities (politically equal to a province) directly under the jurisdiction of the central government, while Urumqi is the capital city of Xinjiang Uygur Autonomous Region (the largest provincial level administrative division in China). The total population of these four cities was nearly 80 million in 2014, accounting more than 1% of the world population.

Beijing is the capital of China and locates in the northern part of the North China Plain, covering an area of 16,410.5 km^2. It had a population of 21.5 million and a gross domestic product (GDP) of 2133 billion RMB[2] (320 billion US Dollar) in 2014 (Beijing Statistics Bureau, 2015). Chongqing locates in the upper reaches of the Yangtze River in southwestern China. It is the solely provincial level municipal city in western China and covers an area of 82,402.9 km^2. In 2014, its GDP and population reached up to 1426 billion RMB (214 billion US Dollar) and 29.9 million, respectively (Chongqing Statistics Bureau, 2015). Shanghai locates in the Yangtze Delta region in southeastern China, covering an area of 6340.5 km^2. It is one of China's most important economic centers with a population of 24.3 million and a GDP of 2357 billion RMB (354 billion US Dollar) in 2014 (Shanghai Statistics Bureau, 2015). Urumqi locates in the northwestern China, covering a total area of about 13,788 km^2. Urumqi is the political and economic center of Xinjiang, with a GDP of 246 billion RMB (37 billion US Dollar) and a population of 3.53 million in 2014 (Urumqi Statistics Bureau, 2015). The selection of these four cities is rational since they locate in different parts of China and have different economic and cultural perspectives.

2.2. Indicator system for CE assessment

2.2.1. Review of CE assessment

The assessment of CE mainly includes two aspects, namely, by a

[1] Data source: http://www.ndrc.gov.cn/zcfb/zcfbtz/zcfbtz2005/t20051101_47934.htm, http://hzs.ndrc.gov.cn/newgzdt/t20071217_179691.htmlatest accessed on March 3, 2013.

[2] RMB is Chinese currency, 1 US Dollar = 6.66 RMB in June 2016.

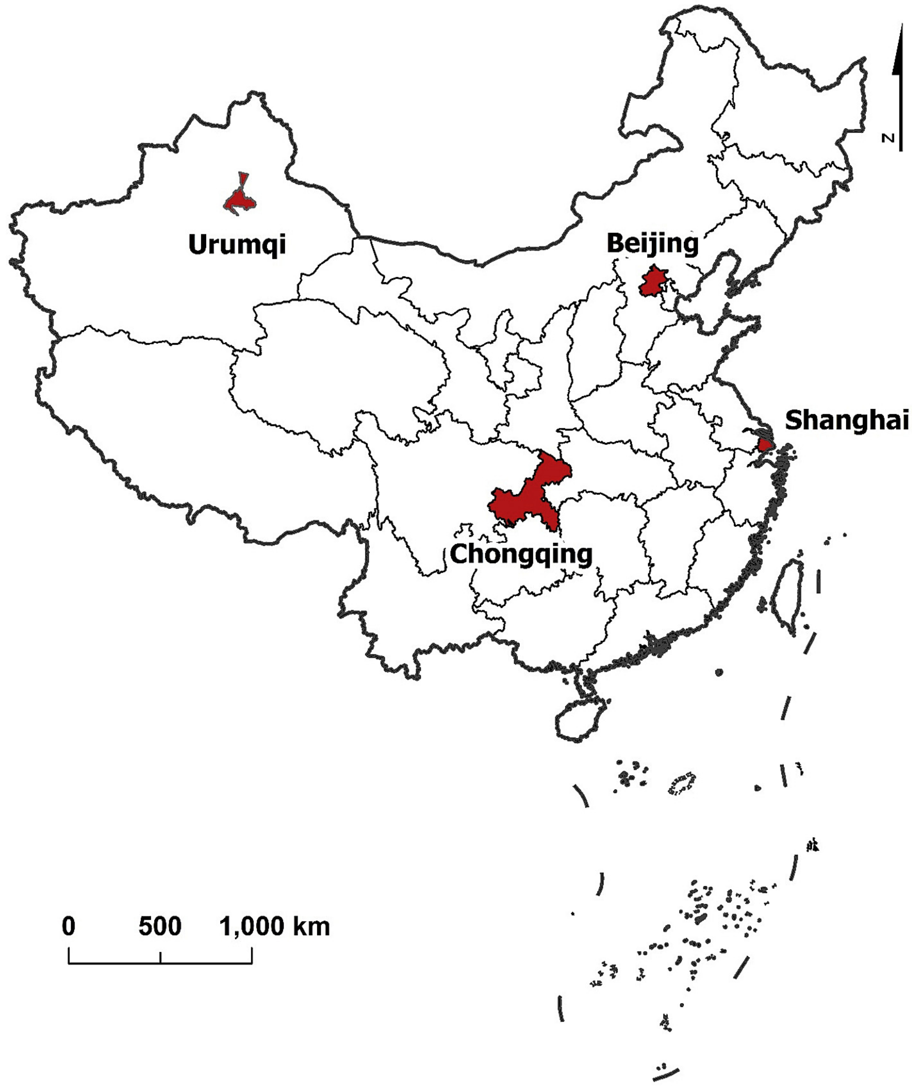

Fig. 1. Location of Beijing, Chongqing, Shanghai and Urumqi.

set of appropriate CE indicators and by the DEA method (Wu et al., 2014; Zeng et al., 2009). The existing studies cover different levels, including macro-level, meso-level and micro-level, especially for different regions and cities (Zeng et al., 2009). Key methods for assessing CE development include material flow analysis, life cycle analysis, eco-efficiency, and emergy (Geng et al., 2013; Su et al., 2013; Zeng et al., 2009). In order to achieve the objective of comprehensive assessment on CE development in China's four megacities, it is essential to establish a unified and complete CE assessment indicator system. Although both governmental agencies and scholars have intensely studied how to promote unified programmatic indicators, different CE implementation levels require different assessment indicators (Su et al., 2013). In 2007 NDRC published Chinese Circular Economy Evaluation Indicator System, including two separate sets of indicators (Geng et al., 2012). One set of indicators is used at macro-level for the general evaluation of CE development of each individual region and the whole country. The other set of indicators is used at meso-level for assessing the status of CE development of industrial parks (Geng et al., 2012). The macro-level CE evaluation indicator system includes 22 indicators, which are categorized into 4 groups, namely resource output, resource consumption, resource comprehensive utilization, and waste emission (Table 1). A detailed explanation of this CE indicator system was conducted by Geng et al. (2012), including the interpretation of indicators and the critical analysis of its advantages and shortcomings. Although some weak points exist, such a CE indicator system can provide objective and credible information on the status of CE implementation at various levels, so as to help decision-makers clarify and reach their desired outcomes (Geng et al., 2012). In order to further improve the effectiveness of such indicators, a new CE evaluation indicator system was released by NDRC in 2017, including 3 indicator groups and 17 indicators. This new indicator system mainly focuses on the evaluation of CE development at national and provincial level, so it is not discussed in this study.

In 2015, China's National Bureau of Statistics (CNBS) established another set of CE indicators to evaluate the CE development status for the whole country (National Bureau of Statistics of China, 2015). This CNBS's CE indicator system includes 4 categories and 16 indicators (Table 2). Comparing with the first set, several improvements were made in this new CE indicator system. For instance, a new category named "waste disposal rate" was established, so that the status of waste disposal, which is a key aspect of CE development, could be examined. In addition, the indicators related to

Table 1
CE evaluation indicator system by NDRC (at macro-level).

Categories	No.	Indicators
1. Resource output indicators	1.1	Output rate of key mineral resources
	1.2	Output rate of energy
2. Resource consumption indicators	2.1	Energy consumption per GDP
	2.2	Energy consumption per unit of industrial added value
	2.3	Energy consumption of unit key products in major industrial sectors
	2.4	Water consumption per GDP
	2.5	Water consumption per unit of industrial added value
	2.6	Water consumption of unit key products in major industrial sectors
	2.7	Coefficient of irrigation water effective utilization
3. Resource comprehensive utilization indicators	3.1	Rate of industrial solid waste comprehensive utilization
	3.2	Rate of industrial water reuse
	3.3	Rate of reclaimed municipal wastewater recycling
	3.4	Rate of municipal solid waste safe disposal
	3.5	Rate of iron scrap recycling
	3.6	Rate of non-ferrous metal recycling
	3.7	Rate of waste paper recycling
	3.8	Rate of waste plastic recycling
	3.9	Rate of waste rubber recycling
4. Waste emission indicators	4.1	Amount of industrial solid waste disposal
	4.2	Amount of industrial wastewater discharge
	4.3	Amount of SO_2 emission
	4.4	Amount of COD discharge

Table 2
CE evaluation indicator system by CNBS (at macro-level).

Categories	No.	Indicators
1. Resource consumption intensity	1.1	Energy consumption per GDP
	1.2	Metal consumption per GDP
	1.3	No-metal resource consumption per GDP
	1.4	Biomass consumption per GDP
	1.5	Water consumption per GDP
2. Waste emission intensity	2.1	Wastewater discharge per GDP
	2.2	Industrial solid waste generation per unit of industrial added value
	2.3	Municipal solid waste generation per capita
	2.4	Key pollutants emission/discharge per GDP
3. Waste recycling and utilization rate	3.1	Rate of energy recycling
	3.2	Rate of industrial water reuse
	3.3	Rate of waste and used resources recycling
	3.4	Rate of industrial solid waste comprehensive utilization
4. Waste disposal rate	4.1	Rate of municipal wastewater treatment
	4.2	Rate of municipal solid waste safe disposal
	4.3	Rate of key pollutants elimination

waste disposal and pollutant emission/discharge were changed from absolute indicators to relative ones. For example, the indicator of “amount of industrial wastewater discharge” was changed to “wastewater discharge per GDP”. Since these relative indicators are comparable, they are preferable for conducting a comparison study on CE development among different regions although they cannot reflect the absolute increase or decrease of wastes or pollutants.

Table 3
CE assessment indicator system of this study.

Dimensions	No.	Indicators
1. Resource consumption intensity (RCI)	1.1	Energy consumption per GDP
	1.2	Energy consumption per unit of industrial added value
	1.3	Water consumption per GDP
	1.4	Water consumption per unit of industrial added value
2. Waste emission intensity (WEI)	2.1	Industrial solid waste generation per unit of industrial added value
	2.2	Municipal solid waste generation per capita
	2.3	Wastewater discharge per GDP
	2.4	Key pollutants emission/discharge per GDP
3. Waste recycling and utilization rate (WRUR)	3.1	Rate of industrial solid waste comprehensive utilization
	3.2	Rate of industrial water reuse
	3.3	Rate of reclaimed municipal wastewater recycling
4. Waste disposal rate (WDR)	4.1	Rate of municipal solid waste safe disposal
	4.2	Rate of municipal wastewater treatment
	4.3	Rate of industrial wastewater COD elimination
	4.4	Rate of industrial SO_2 elimination

2.2.2. Establishment of CE assessment indicator system

The CE assessment indicator system developed in this study was based upon the CNBS's CE evaluation indicator system. Since the four categories of resource consumption, waste emission, waste recycling and utilization, and waste disposal are the four representative aspects of CE development, this study employs the same four categories for establishing a CE assessment indicator system (Table 3). The first category, namely resource consumption intensity (RCI), consists of four indicators. Two indicators, namely “energy consumption per GDP” and “water consumption per GDP”, are derived from CNBS's CE evaluation indicator system, while other two indicators, “energy consumption per unit of industrial added value” and “water consumption per unit of industrial added value”, are derived from NDRC's CE evaluation indicator system. Therefore, the energy and water consumption intensity of both at the city level and at the sectoral level can be examined. The second category, waste emission intensity (WEI), employs four indicators, which are exactly the same as those from CNBS, covering emission intensity of industrial solid waste, municipal solid waste, wastewater and key pollutants. Key pollutants include COD, SO_2, and soot and dust derived from both industrial and residential sources. As to the third category, waste recycling and utilization rate (WRUR), two indicators “rate of industrial solid waste comprehensive utilization” and “rate of industrial water reuse” from CNBS, as well as one indicator of “rate of reclaimed municipal wastewater recycling” from NDRC are included. The fourth category, waste disposal level (WDL), includes four indicators of “rate of municipal solid waste safe disposal”, “rate of municipal wastewater treatment”, “rate of industrial wastewater COD elimination” and “rate of industrial SO_2 elimination” from CNBS. The detailed calculation methods of all CE indicators are listed in Table 4.

2.3. Accounting method

2.3.1. Data normalization

The proposed CE assessment indicator system includes both positive indicators and negative indicators. Those indicators that the higher values can represent better CE development are defined as the positive indicators, such as the indicators in categories 3 and 4. In contrast, those indicators that the lower values represent better CE development are defined as the negative indicators, such as these indicators in categories 1 and 2. In order to make all the

Table 4
Calculation formula and weights of CE indicators.

No.	Calculation formula	Weight
1.1	Energy consumption per GDP = total energy consumption/GDP	0.079
1.2	Energy consumption per unit of industrial added value = industrial energy consumption/industrial added value	0.065
1.3	Water consumption per GDP = total water consumption/GDP	0.047
1.4	Water consumption per unit of industrial added value = industrial water consumption/industrial added value	0.059
2.1	Industrial solid waste generation per unit of industrial added value = industrial solid waste generation/industrial added value	0.072
2.2	Municipal solid waste generation per capita = municipal solid waste generation/permanent resident population	0.039
2.3	Wastewater discharge per GDP = total wastewater discharge/GDP	0.056
2.4	Key pollutants emission/discharge per GDP = total amount of key pollutants emission/GDP	0.084
3.1	Rate of industrial solid waste comprehensive utilization = industrial solid waste comprehensive utilization/industrial solid waste generation	0.029
3.2	Rate of industrial water reuse = industrial water reuse/total industrial water consumption	0.042
3.3	Rate of reclaimed municipal wastewater recycling = municipal wastewater recycling/municipal wastewater treated	0.178
4.1	Rate of municipal solid waste safe disposal = safely disposed municipal solid waste/total municipal solid waste generation	0.065
4.2	Rate of municipal wastewater treatment = municipal wastewater treated/municipal wastewater discharge	0.036
4.3	Rate of industrial wastewater COD elimination = industrial wastewater COD elimination/total industrial wastewater COD generation	0.062
4.4	Rate of industrial SO_2 elimination = industrial SO_2 elimination/total industrial SO_2 generation	0.088

indicators comparable, the normalization of both positive and negative indicators is necessary. Although several methods are available for indicator normalization, the adoption of improper normalization methods might lead to incorrect results (Ye, 2003). According to Ye (2003), mean value method should be applied for the normalization of objective data and it could retain the variance of each indicator after normalization. In this study, in order to reflect the contribution of each indicator to CE development, the variance of each indicator among different years and from different megacities should be retained after normalization. Consequently, the mean value method was adopted for indicators normalization, which means the average values of each indicator for all the four megacities from 2005 to 2014 were employed.

For each megacity, the positive indicators can be normalized by using Eq. (1):

$$x'_{ij} = \frac{x_{ij}}{\bar{x}_i} \tag{1}$$

Similarly, the negative indicators can also be normalized by using Eq. (2):

$$x'_{ij} = \frac{\bar{x}_i}{x_{ij}} \tag{2}$$

where, x'_{ij} denotes the value of indicator i in the year j after normalization; x_{ij} denotes the original value of indicator i in the year j before normalization; $\bar{x}_i$ denotes the average original value of indicator i in four megacities from 2005 to 2014.

2.3.2. *Weights determination*

After normalization, the next step is to determine the weight of each indicator before aggregation. Approaches for determining weights could be classified into subjective approaches and objective approaches. The subjective approaches, including average weighting method, eigenvector method, weighted least square method, and Delphi method, define weights on the basis of preference information of attributes given by the decision makers (Ma et al., 1999; Su et al., 2013). In contrast, the objective approaches, which include principal element analysis, entropy method, multiple objective programming, determine weights based on the objective information, such as numerical decision matrixes (Ma et al., 1999). Both subjective approaches and objective approaches have their drawbacks and limitations. For instance, the analytical results derived from subjective weighting methods might be influenced by the knowledge and experience of decision makers, while objective approaches might neglect the useful subjective judgement information (Ma et al., 1999). In order to better reflect both subjective and object information, an integrated weighting approach, incorporating the advantages of both subjective and object approaches, is preferable. Average weighting method, with the feature of unsophisticated accounting process, was used by Li and Zhang (2005) for determining the weight of CE indicators in a CE evaluation study for one resource based city. Entropy method, which determines the weight of indicators by measuring the amount of useful information that the objective data provided (Qiu, 2002; Zou et al., 2006), have been widely used in environmental studies. Especially, it was adopted by the Chinese local authority for the determination of the weight of indicators for CE development evaluation (Shaanxi Provincial Bureau of Statistics, 2015; Zou et al., 2006). Consequently, an integrated approach combining both average weighting method and entropy method was employed to determine the weight of each indicator in this study. First, the four categories of CE, namely, RCI, WEI, WRUR and WDL, were considered as four equal important aspects and were assigned the same weight. Then the weights of indicators in each category were determined by the entropy method. The accounting procedures of entropy method include the followings (Qiu, 2002; Zou et al., 2006):

1) Normalization of the original evaluation matrix

The original indicator value matrix in each category $A = (a_{ij})_{m\times n}$ is transformed to normalized indicators value matrix $R = (r_{ij})_{m\times n}$ by the following two equations:

For positive indicators,

$$r_{ij} = \frac{a_{ij} - \min_j\{a_{ij}\}}{\max_j\{a_{ij}\} - \min_j\{a_{ij}\}} \tag{3}$$

For negative indicators,

$$r_{ij} = \frac{\max_j\{a_{ij}\} - a_{ij}}{\max_j\{a_{ij}\} - \min_j\{a_{ij}\}} \tag{4}$$

where, m denotes the amount of indicators in each dimension; n denotes the amount of research years; r_{ij} denotes the normalized value of indicator i in the year j; a_{ij} denotes the original value of indicator i in the year j before normalization.

2) Definition of the entropy

The entropy with respect to each indicator is defined as following:

$$e_i = -k\sum_{j=1}^{n} f_{ij}\ln f_{ij} \tag{5}$$

where, e_i denotes the entropy with respect to indicator i; $f_{ij} = \frac{r_{ij}}{\sum_{j=1}^{n} r_{ij}}$; $k = 1/\ln n$;. One assumption is made, namely, when $f_{ij} = 0$, $f_{ij}\ln f_{ij} = 0$.

3) Definition of the weight of entropy

The entropy weight of each indicator is defined as following:

$$w_i = \frac{1-e_i}{m-\sum_{i=1}^{m} e_i} \tag{6}$$

where, w_i denotes the weight of entropy of indicator i; and $0 \le w_i \le 1$, $\sum_{i=1}^{m} w_i = 1$.

In this study, each CE indicator should have the same weight for different megacities to ensure that the results from four different megacities are comparable. In order to achieve this, the values of all the indicators in each category from all the four megacities were compiled together to form a new indicators value matrix before normalization, which includes all the data of each category in four megacities from 2005 to 2014, by means of keeping the amount of indicators (namely, the number of rows) unchanged and combining the columns of four megacities. This new indicator value matrix, adopted for determining the weight of each indicator for each category, is presented as following:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1b} & a_{1c} & \cdots & a_{1d} & a_{1e} & \cdots & a_{1f} & a_{1k} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mb} & a_{mc} & \cdots & a_{md} & a_{me} & \cdots & a_{mf} & a_{mk} & \cdots & a_{mn} \\ & \text{Beijing} & & & \text{Chongqing} & & & \text{Shanghai} & & & \text{Urumqi} & \end{bmatrix} \tag{7}$$

Through the above accounting procedures, the weights of all the CE indicators could be obtained, which is listed in Table 4.

2.3.5. CE development index accounting

In order to shed light on the comprehensive status of CE development, all the CE indicators need to be aggregated according to their weights. The aggregated value of all the CE indicators was named as CE development index, which was employed to explore the CE development status of each megacity. For each megacity, annual CE development index can be determined by using Eq. (8):

$$CE_j = \sum_i x'_{ij}\cdot w_i \tag{8}$$

where, CE_j denotes the CE development index in the year j; x'_{ij} denotes the normalized value of indicator i in the year j; w_i denotes the weight of indicator i.

Similarly, the development index of CE's each category, namely, RCI, WEI, WRUR and WDL, could be calculated by aggregating the CE indicators within its category, so that the contribution of CE's each category could be identified, and the structure of CE development index could be presented.

2.4. Data sources

Data used for this study were mainly derived from statistics yearbooks of these four megacities and China Environment Yearbooks 2006–2015. Data related to Chongqing municipal solid waste were derived from “Communique on the State of the Environment in Chongqing” which was published annually by Chongqing Environmental Bureau. Date related to water consumption intensity in Shanghai were derived from “Shanghai Key Water Consumption Indicators” report published by Shanghai Water Supply Agency annually. The energy consumption data and water consumption data of Urumqi were collected from statistics report of Urumqi Statistics Bureau and Xinjiang Statistics Yearbooks. Data related to industrial water consumption and reuse derived from China Environmental Yearbooks were from those key investigated industrial enterprises. Since the accounting method of energy consumption data was changed by CNBS in 2013, in order to ensure data consistency, historical energy consumption data before 2013 were calibrated by using the new accounting method. Since the statistical method of industrial wastewater and pollutants was changed in 2011, related historical data before 2011 were calibrated by using the new method. In order to eliminate the inflation effect, GDP values and industrial added values in each megacity were transformed to comparable prices by taking the year 2005 as the baseline year.

3. Research findings

3.1. CE performance in four mega cities

Fig. 2 illustrates the general trends of the eight CE indicators related to RCI and WEI in four megacities for the period of 2005–2014. It is clear that most CE indicators related to RCI and WEI in four megacities had been improved since 2005. For instance, in all four investigated megacities, both water consumption per GDP and water consumption per unit of industrial added value in 2014 were more than 50% less than in 2005. Especially, Chongqing had achieved the reduction of water consumption per unit of industrial added value for more than 75% and the reduction of water consumption per GDP for more than 65%. In addition, energy consumption per unit of industrial added value and energy consumption per GDP had reduced more than 40% and 30% since 2005, respectively. Especially, Beijing had reduced its energy consumption per unit of industrial added value for nearly 60%, and Urumqi had reduced its energy consumption per GDP for around 43%. Such results indicate that all four megacities had adopted positive measures on reducing water and energy consumption.

Also, key pollutants emission/discharge per GDP in all four megacities in 2014 were more than 70% less than in 2005, indicating the enormous improvements of the emission intensity of COD, soot and dust, and SO_2. Besides, wastewater discharge per GDP decreased more than 30% in all four megacities, and industrial solid waste generation per unit of industrial added value also decreased more than 50% in Beijing, Chongqing and Shanghai. However, four megacities had different performance on municipal solid waste generation per capita. While such an amount had been reduced in Urumqi, Beijing and Shanghai, it kept unchanged in Chongqing.

Fig. 3 illustrates the comparison of CE indicators related to WRUR and WDL in four megacities during 2005–2014. In general, most WRUR and WDL indicators had been improved during 2005–2014. Especially, all four megacities made progresses on industrial solid waste comprehensive utilization, the level of which reached more than 80% in Beijing and Chongqing, and more than 90% in Shanghai and Urumqi in 2014. With regard to the rate of industrial water reuse, Beijing and Urumqi had been keeping at a level of more than 90% since 2005. Meanwhile, Chongqing and Shanghai had made more than 20% and 30% increment, and achieved at the level of more than 80% and 90% in 2014, respectively. In contrast, while Beijing had improved nearly 30% on reclaimed municipal wastewater recycling, such a rate in Chongqing and

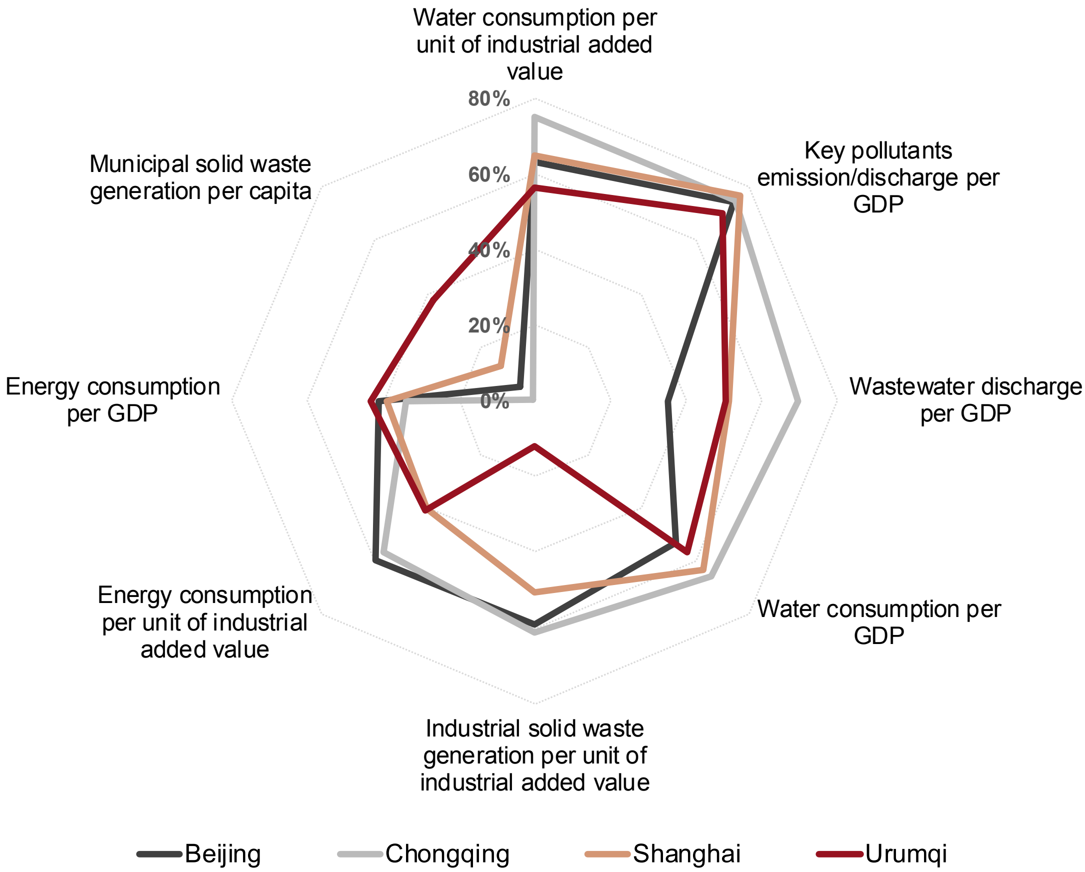

Fig. 2. Comparison of CE improvements related to RCI and WEI from 2005 to 2014.

Shanghai had maintained at a very low level and made little progresses since 2005. Urumqi even experienced a decrease for such a rate.

With respect to waste disposal and pollutant elimination, all WDL related indicators were improved in four megacities. For instance, the rate of industrial SO_2 elimination in all the megacities

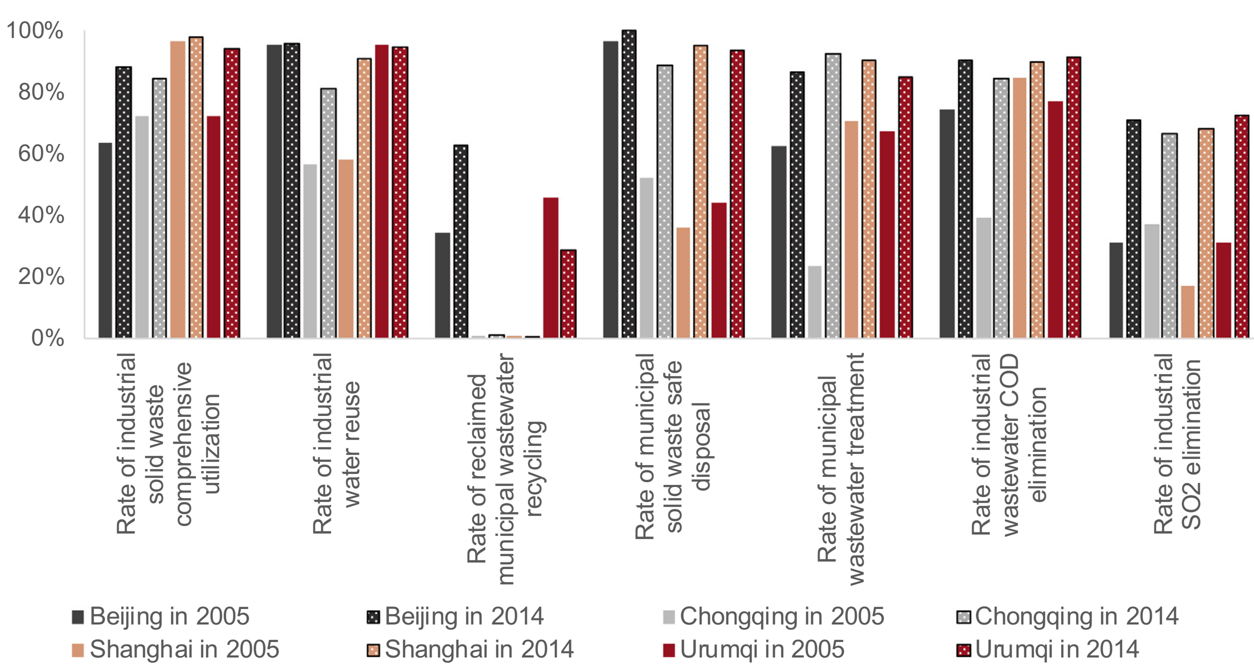

Fig. 3. Comparison of CE indicators related to WRUR and WDR between 2005 and 2014.

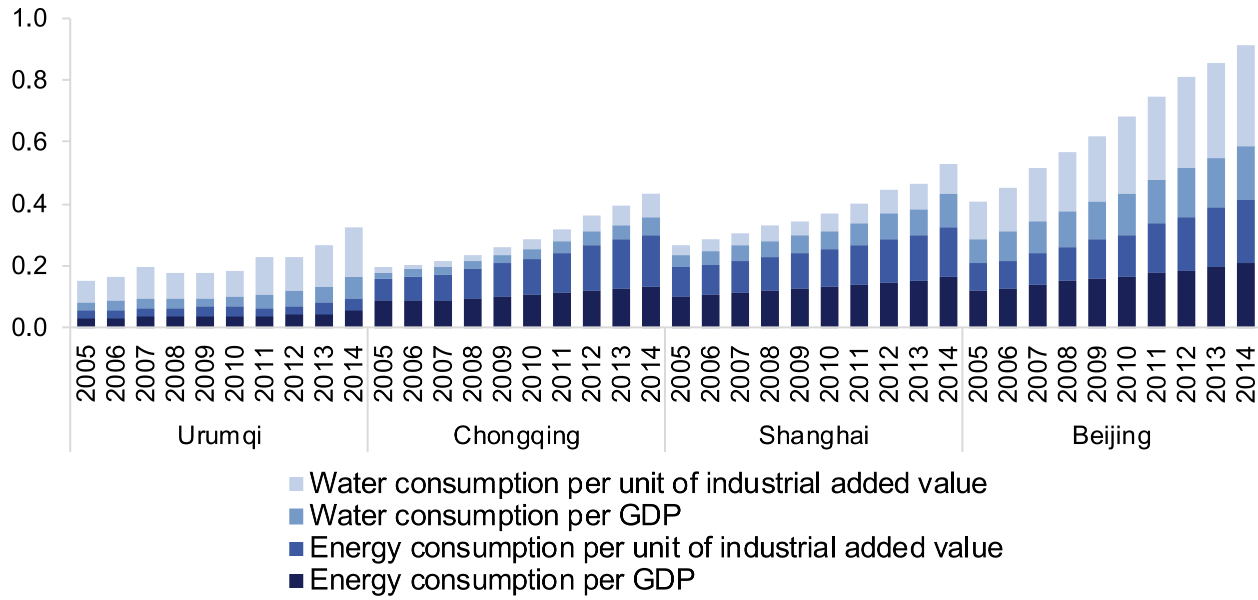

Fig. 4. Comparison of RCI index trajectories in four megacities.

had increased significantly. In particular, it had an increase of more than 50% in Shanghai since 2005. Apart from Beijing which had a better performance on municipal solid waste safe disposal in 2005, all the other three megacities had significantly increased their rates of municipal solid waste safe disposal since 2005. Even though lagging behind on the rate of municipal wastewater treatment and the rate of industrial wastewater COD elimination in 2005, Chongqing caught up with the other three megacities on these two aspects in 2014.

3.2. Resource consumption intensity

Fig. 4 illustrates the results of RCI index trajectories in four megacities for the period of 2005–2014. It is clear that all four megacities had improved their RCI index since 2005, and Beijing had a better RCI performance comparing to the other three megacities. Especially, the RCI index of Beijing in 2005 was better than that of Urumqi in 2014 and that of Chongqing in 2013. Such results indicate that the RCI performance of Chongqing in 2013 and Urumqi in 2014 could only equal to or even worse than the performance of Beijing in 2005, representing more than eight and nine years' gap, respectively. Especially, Urumqi lagged behind on energy consumption per GDP and energy consumption per unit of industrial added value when compared with the other three megacities. In contrast, Chongqing performed better with respect to energy consumption intensity, but not for water consumption

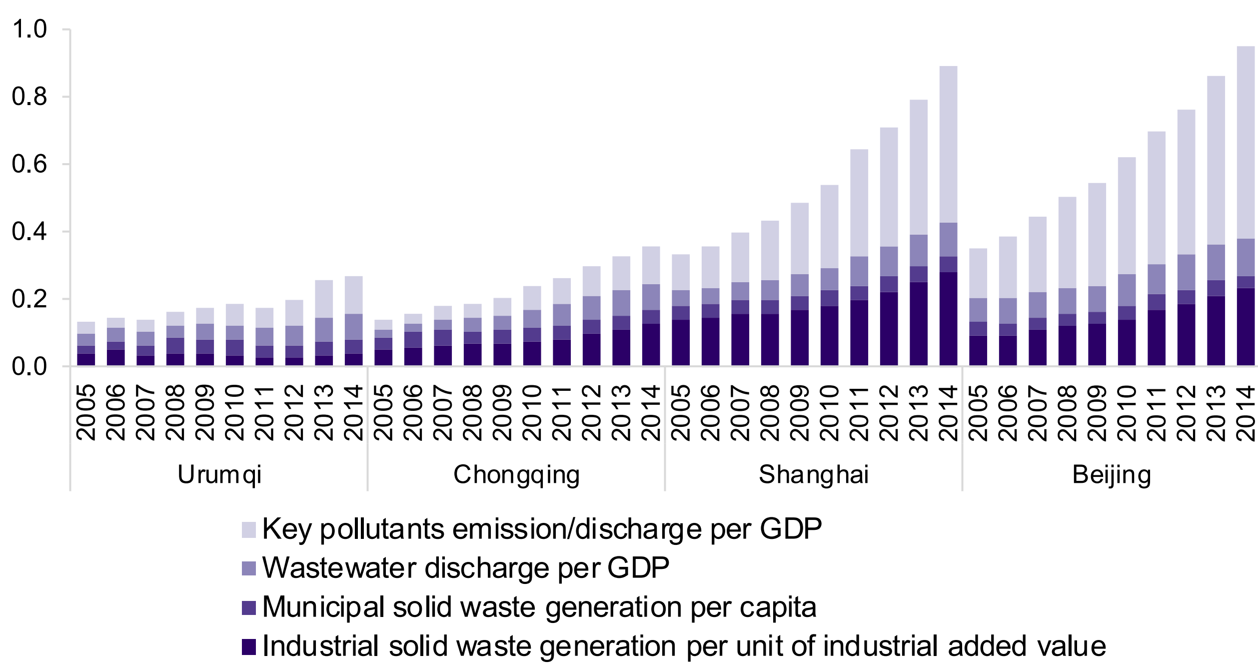

Fig. 5. Comparison of WEI index trajectories in four megacities.

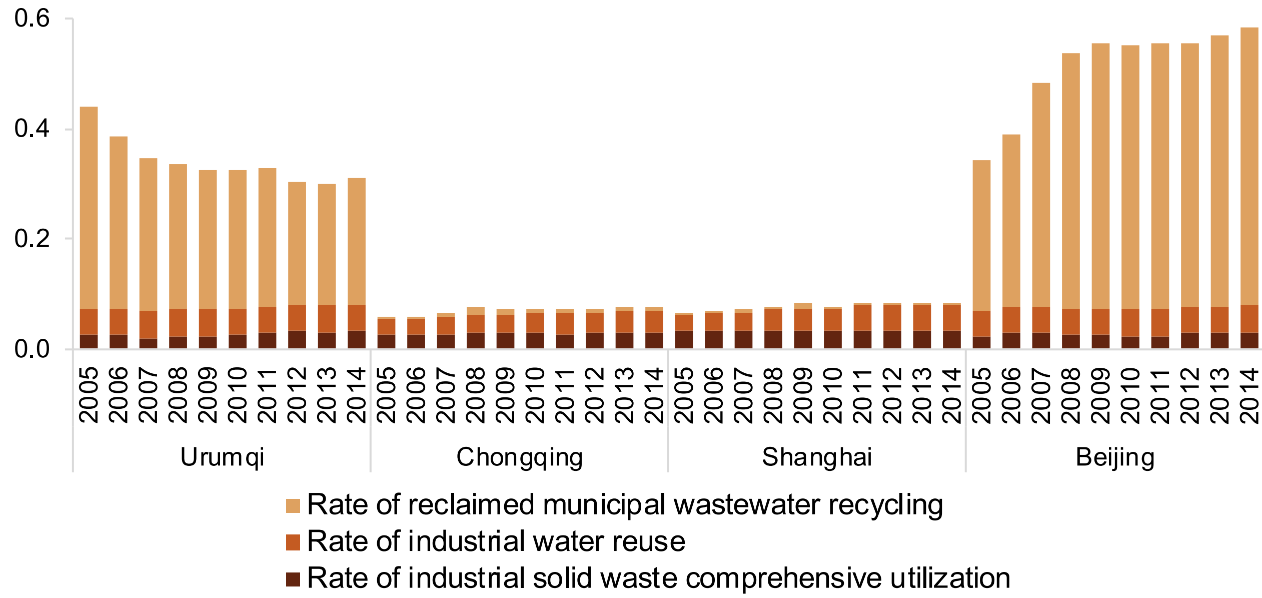

Fig. 6. Comparison of WRUR index trajectories in four megacities.

per GDP and water consumption per unit of industrial added value. Besides, Beijing and Urumqi performed better than Chongqing and Shanghai with regard to water consumption per unit of industrial added value.

3.3. Waste emission intensity

Fig. 5 illustrates the results of WEI index trajectories in four megacities for the period of 2005–2014. In general, Beijing and Shanghai performed better than Chongqing and Urumqi with regard to WEI performance, as well as WEI improvements during 2005–2014. Urumqi had the worst WEI performance, especially, with respect to the indicator of industrial solid waste generation per unit of industrial added value which had both the lowest level and least improvement. In contrast, Shanghai and Beijing performed better on industrial waste intensity with both higher level and continuous improvements. As for Chongqing, high intensity of key pollutants emission/discharge and wastewater discharge limited its WEI level from 2005 to 2009. In addition, Beijing and shanghai had better performances on key pollutants emission/discharge per GDP, showing great improvement since 2005 and with a higher level in 2014.

3.4. Waste recycling and utilization rates

Fig. 6 presents the results of WRUR index trajectories in four megacities during 2005–2014. Generally, Beijing and Urumqi had much better performance on WRUR than Chongqing and Shanghai. However, the increase of WRUR index in Beijing had been very slow since 2008, and the WRUR index in Urumqi had showed a decrease

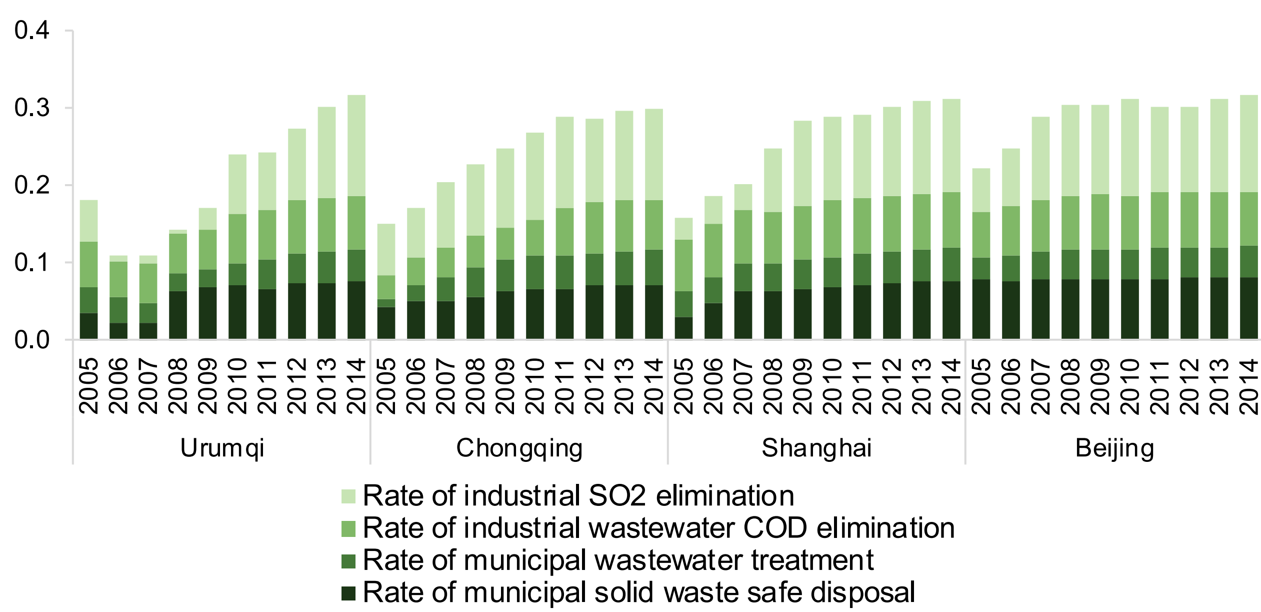

Fig. 7. Comparison of WDR index trajectories in four megacities.

trend since 2005. In addition, the WRUR index in Chongqing and Shanghai had little improvement during 2005–2014, especially with regard to the rate of reclaimed municipal wastewater recycling. In contrast, Beijing and Urumqi had much better performance than Chongqing and Shanghai with regard to the rate of reclaimed municipal wastewater recycling, as well as the rate of industrial water reuse. Additionally, Shanghai did better than the other three megacities with respect to the rate of industrial solid waste comprehensive utilization.

3.5. Waste disposal level

The results of trajectories of WDL index in four megacities from 2005 to 2014 are illustrated in Fig. 7. Generally, during 2005–2014, all the four megacities had improved their WDL performance and gaps among their WDL performance had been narrowed gradually. For instance, most of the improvements occurred in Urumqi and Chongqing before 2012 and in Beijing and Shanghai before 2008. Especially, the WDL index of Chongqing and Urumqi had increased remarkably. The lower WDL in Chongqing was mainly resulted from the lower rate of industrial wastewater COD elimination before 2010, and the lower rate of municipal solid waste safe disposal and municipal wastewater treatment before 2007. As for Urumqi, the lower rate of industrial SO_2 elimination from 2006 to 2009, the lower rate of municipal solid waste safe disposal from 2005 to 2007, and the lower rate of municipal wastewater treatment before 2010 were the key factors that contribute to its lower WDL performance. In addition, the levels of industrial SO_2 elimination from 2005 to 2007 and municipal solid waste safe disposal from 2005 to 2006 were also low in Shanghai. However, they were improved quickly afterwards and kept the same level as in Beijing after 2009.

3.6. CE development trajectory

The trajectories and compositions of four megacities' CE development index are presented in Fig. 8. It is obvious that Beijing had the best CE performance, which was much better than the other three megacities. Especially, CE development indexes of Urumqi and Chongqing in 2014 were lower than the CE development index of Beijing in 2005, indicating a more than nine years gap of CE development. Furthermore, while CE development indexes in Beijing, Chongqing and Shanghai had been increasing continuously since 2005, CE development index in Urumqi was unstable. Urumqi's CE development index decreased from 2005 to 2007, then kept stabile from 2007 to 2009, and finally increased from 2009. In addition, the high CE development index in Beijing was contributed by CE's all four categories, namely RCI, WEI, WRUR and WDL, indicating its comprehensive CE development in Beijing. However, CE development indexes in Chongqing and Shanghai were mostly contributed by the three categories of RCI, WEI and WDL, but with less contribution from WRUR, indicating the requirement on further improvement of WRUR performance. As for CE development in Urumqi, contributions from three categories of RCI, WEI and WRUR were quite limited, which need to be improved in the future.

Fig. 9 illustrates the CE performance and CE development index growth rates of the four megacities, together with the locations of these megacities in China. It is obvious that megacities located in eastern China, namely Beijing and Shanghai, had better CE development performances than those in megacities from western China, namely Urumqi and Chongqing. While Beijing had much better CE development performance than the other three megacities, CE development performances in Urumqi and Chongqing were lower than the average level of four megacities, and CE

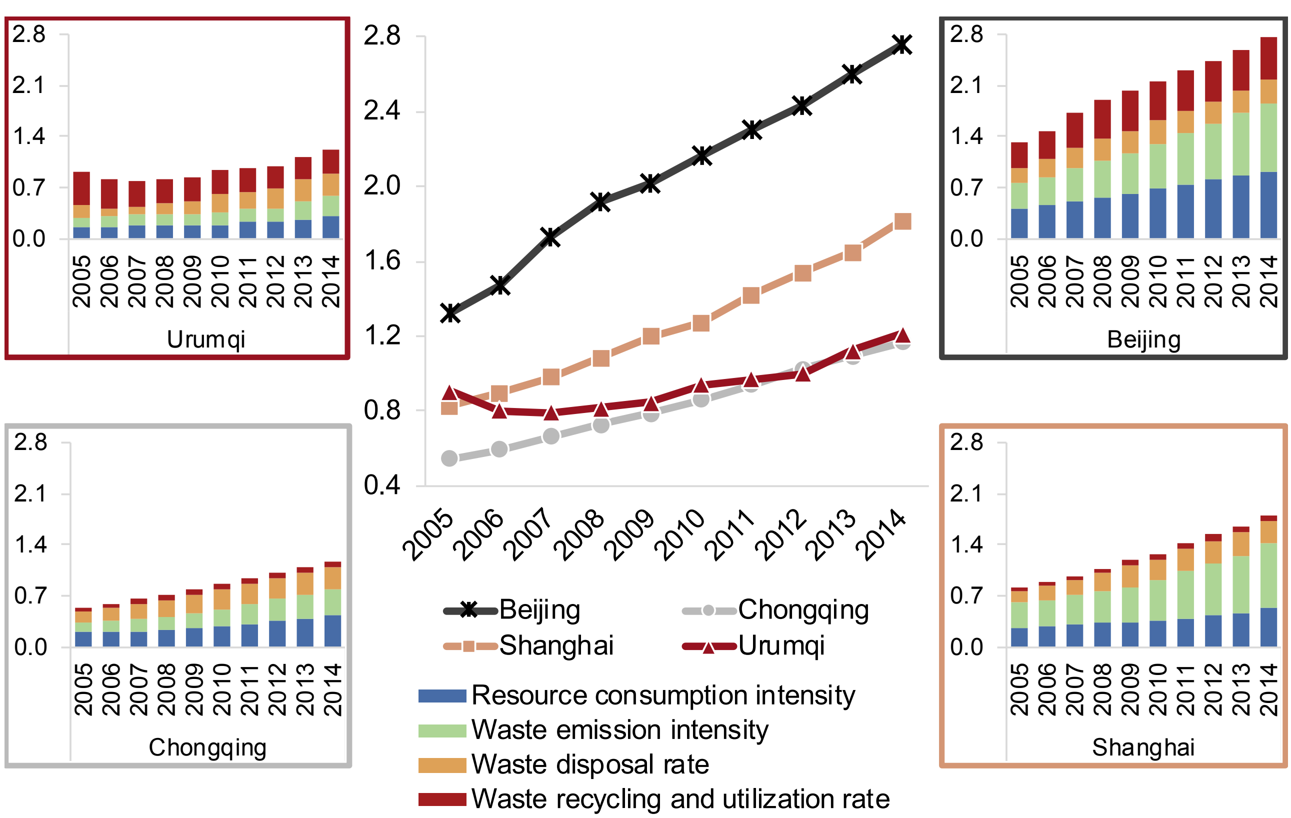

Fig. 8. Comparison of CE development index trajectory and composition.

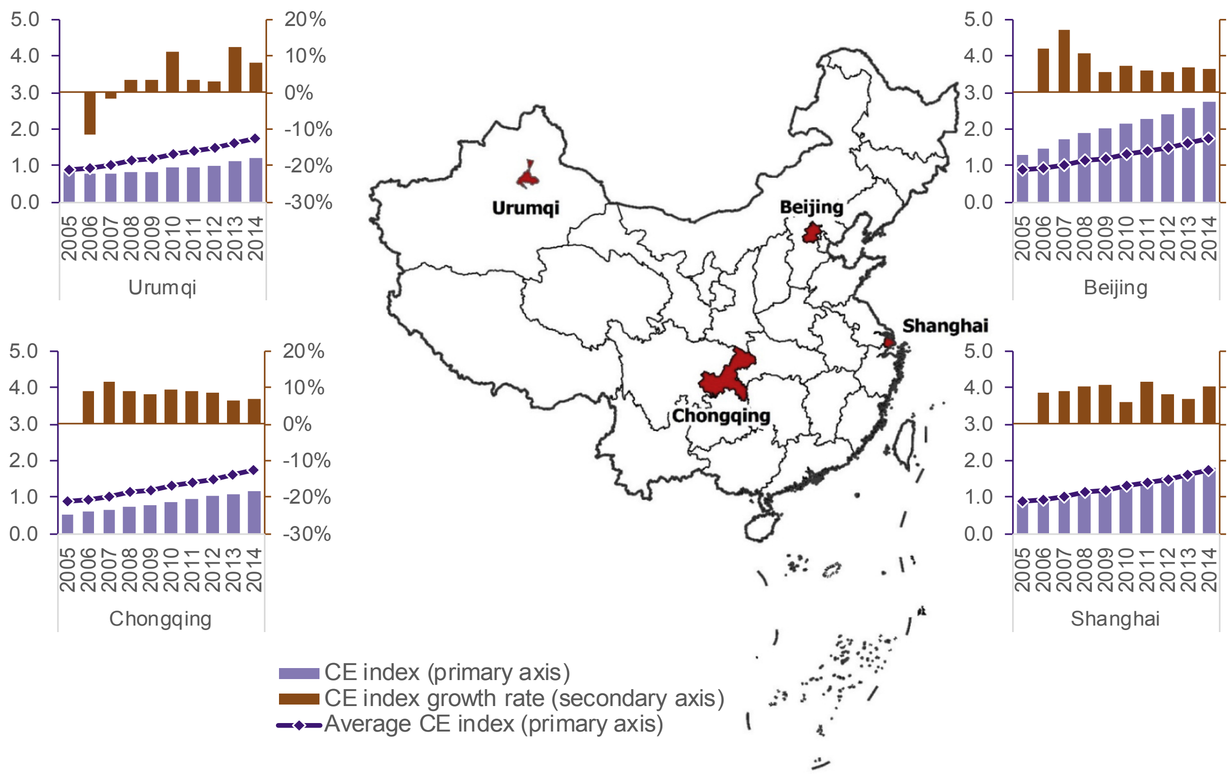

Fig. 9. CE development index trajectory and growth rates in four mega cities.

performance in Shanghai was almost the same as four megacities' average. In addition, the growth rates of CE development indexes in Beijing, Chongqing and Shanghai were more stable than those of Urumqi. Especially, Shanghai had the highest annual growth rate of CE development indexes between 2005 and 2014, with a figure of around 9.1% per year. With regard to Beijing, the growth rate of CE development indexes increased rapidly between 2005 and 2008, with a figure of more than 10% per year. Since then it had kept at a lower level of around 6.3% per year. Furthermore, the CE development index of Urumqi first decreased between 2005 and 2007, and increased afterwards. Thus, the annual growth rate of CE development in Urumqi, with a figure of around 3.3% per year, was lower than those in the other three megacities.

4. Discussions

Research results from this study indicate that significant disparities exist among China's four megacities with respect to CE development performance and structure. Especially, CE development in Urumqi had both a lower development level and a slower increasing trend. High resource consumption intensity and high waste emission intensity were the two key factors that hindered the CE development in Urumqi. In particular, more attentions should be paid to mitigate the high energy consumption intensity, the high discharge intensity of industrial solid waste and industrial wastewater, and the high emission intensity of pollutants, such as soot and dust, SO_2 and COD in Urumqi. Both Urumqi's local government authorities and China's central government agencies should play the key roles in these aspects. For instance, Urumqi municipal government should establish more detailed action plans on the basis of current energy conservation and emission reduction targets, as well as setting more ambitious energy conservation and emission reduction targets by learning the experiences from other megacities. In addition, in order to support the implementation and accomplishment of action plans and activities in Urumqi, financial and technological supports from central government are of vital importance. In fact, Urumqi just received a three years' financial subsidy from Chinese central government for promoting local energy conservation and emission reduction, which started from 2015 with an amount of 1.5 billion RMB (225 million US dollar) in total. According to the reports from both Urumqi Development and Reform Commission and Ministry of Finance of China,[3] several demonstration projects related to energy conservation and emission reduction were initiated, including the utilization of renewable energy, the reduction of key pollutants, the promotion of energy efficient buildings, the promotion of clean energy vehicles, etc. However, more supports from central government in broader manners are still required since Urumqi is far lagging behind other three megacities in terms of economic development. In this regard, the west development project proposed by the central government may be one potential source. It will require the local government to prepare a more ambitious regional development plan so that such energy saving and emission reduction efforts can be incorporated into the overall development plan. In addition, the application of state of the art technologies is also essential for improving CE development in Urumqi. CE related technologies, which have been effectively applied in other cities or regions, should be transferred to Urumqi by considering the local realities, such as energy and water cascading technologies, advanced process integration technologies, as well as environmentally friendly infrastructure (Geng

[3] Data source: http://www.urumqidrc.gov.cn/content/jnjc/402882885590218601560658a2960034.html, latest access on July 26, 2016; http://www.mof.gov.cn/zhengwuxinxi/caijingshidian/zgcjb/201512/t20151228_1634914.html, latest access on July 26, 2016.

et al., 2013).

As for Shanghai and Chongqing, the high water consumption intensity and the low water recycling rates were the two key factors that hindered their CE development. Both of them locate close to the Yangtze River and have rich water resource. However, the water quality has become key concerns due to serious water pollution (Meng and Yu, 2004). According to *the 12*th *five-year plan for China's cities and towns on the construction of wastewater treatment and recycling facilities*,[4] the average recycling rate of municipal wastewater should reach 15% in 2015. Thus, it is realistic and imperative for Shanghai and Chongqing to improve their water consumption intensity and promote the recycling of reclaimed municipal wastewater. Since the sewage treatment plants in Shanghai receive wastewater from both domestic and industrial sources, it is essential to require those industrial companies to pre-treat their wastewater inside their facilities and also seek the potential reuse or recycling opportunities among different industrial water users (Geng et al., 2007; Ma et al., 2015). Plus, advanced wastewater treatment technologies, such as ozone treatment technology, membrane separation technology and biological treatment technology, should be applied (Ma et al., 2015).

In addition, all four megacities had made great progresses on waste treatment since 2005. Especially, the rate of municipal solid waste safe disposal in Shanghai had increased by 60%, from 35.7% in 2005 to 95% in 2014. However, such a great improvement might not be on the basis of effective and efficient waste management. One example is that eight vessels from Shanghai dumped 4000 tons of garbage on the banks of the Taihu lake in the Suzhou Taihu National Tourism Vacation Zone in Jiangsu province, a neighbor province of Shanghai (Wei, 2016). More seriously, this was not the first time that the local residents in Jiangsu found such irrational garbage dump from Shanghai, which induced a serious concern of not-in-my-backyard. Obviously, such a manner of waste treatment could only transfer the pollutions from one city to another, but not reduce the overall amount of municipal wastes. Therefore, it is crucial to promote an integrated waste management approach, which considers the entire process of waste treatment, including waste separation, collection, transportation, recycling and final disposal. All of these waste treatment processes should be carried out under the supervision of the local authority so that the illegal treatment and disposal of municipal wastes could be avoided. In addition, local residents in Jiangsu played a key role on the prevention of illegal waste dumping, which implies that the participation of local residents is another essential aspect for CE promotion. Thus, more information related to CE development should be disclosed and provided to local residents through newspapers, pamphlets and TV programs so as to promote the public participation during the CE development process. Such efforts might help local residents to improve their day-to-day behaviors, such as household waste separation and minimization, household water recycling and reutilization, the adoption of public transportation or the purchase of new energy vehicles, etc.

Although this study provided valuable information for policy makers to further promote their local CE development, limitations exist. For instance, duo to data limitations, indicators related to energy cascading, economic benefits of waste recycling, as well as indicators related to intensity of metal, non-metal and biomass consumption are not included in this study. Besides, in order to make sure that the results of selected indicators from four different megacities are comparable, only relative indicators are selected. Absolute indicators, such as GDP, total waste emissions, total water recycling amounts, were not included. Last but not the least, this study only chose four megacities for the comparison study, not covering the CE development features of all the megacities in China. Future CE assessment studies may choose more cities or regions, as well as including more recycling based indicators, so that more complete information related to CE development in the Chinese cities and regions could be released.

[4] Data source: http://www.gov.cn/zwgk/2012-05/04/content_2129670.htm, latest access on July 26, 2016.

5. Conclusions

Circular Economy, adopted by the Chinese central government as the national development strategy for mitigating resources scarcity and reducing environmental pollution, is of major importance for pursuing sustainable development. This study assesses and compares the CE development in China's four megacities, namely Beijing, Chongqing, Shanghai and Urumqi, for the period of 2005–2014. Key research findings include:

1) Most of the CE indicators in four megacities had been improved during 2005–2014. Especially, key pollutants emission/discharge per GDP in all four megacities in 2014 were more than 70% less than in 2005, and water consumption intensity and energy intensity in the four megacities were improved by more than 50% and more than 30% during the same period. However, there was little improvement regarding the indicator of reclaimed municipal wastewater recycling in Chongqing and Shanghai.
2) Beijing had higher RCI index than the other three megacities, while both Urumqi and Chongqing were much backward. Besides, Beijing and Shanghai had better WEI performance than Chongqing and Urumqi, and Urumqi and Beijing did better than Chongqing and Shanghai with respect to WRUR performance. In general, all the four megacities had improved their WDL performance and gaps among their WDL performance had been narrowed.
3) Significant disparities exist among China's four megacities with respect to CE development performances. While all the four megacities had significantly improved their CE development level since 2005, megacities located in eastern China, namely Beijing and Shanghai, had better CE development performance than megacities from western China, namely Urumqi and Chongqing, due to their advanced technologies and better management.
4) Beijing and Urumqi performed better on balancing the development of CE's four categories, namely, RCI, WEI, WRUR and WDL. In contrast, CE development in Chongqing and Shanghai was primarily attributed to the three categories of RCI, WEI and WDL, and the WRUR category had contributed little to their CE development, indicating an unbalanced CE development status.
5) Annual average CE development performances in Shanghai and Chongqing increased faster than Beijing and Chongqing during 2005–2014, and the improvement of CE development in Urumqi was the slowest among the four megacities.

On the basis of the above results, several policy suggestions that addressing the specific local situations of each megacity, were proposed, such as providing financial and technological support to Urumqi and Chongqing, promoting the recycling of reclaimed wastewater in Chongqing and Shanghai, supporting the application of integrated waste management approach, as well as encouraging the participation of local residents. Results derived from this study can provide valuable policy insights to those decision-makers so that more appropriate policies can be made by considering the local realities.

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References

Beijing Municipal Bureau of Statistics, 2015. Beijing Statistical Yearbook. China Statistics Press, Beijing.
Bilitewski, B., 2008. Circular economy: balancing development and environmental protection. In: Proceedings of the 2nd International Conference on Asian-european Environmental Technology and Knowledge Transfer, pp. 1–7.
Chongqing Municipal Bureau of Statistics, 2015. Chongqing Statistical Yearbook. China Statistics Press, Beijing.
Geng, Y., Cote, R., Tsuyoshi, F., 2007. A quantitative water resource planning and management model for an industrial park level. Reg. Environ. Change 7, 123–135.
Geng, Y., Doberstein, B., 2008. Developing the circular economy in China: challenges and opportunities for achieving 'leapfrog development'. Int. J. Sust. Dev. World 15, 231–239.
Geng, Y., Fu, J., Sarkis, J., Xue, B., 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. J. Clean. Prod. 23, 216–224.
Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339, 1526–1527.
Geng, Y., Tsuyoshi, F., Chen, X.D., 2010. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. J. Clean. Prod. 18, 993–1000.
Guo, B., Geng, Y., Sterr, T., Dong, L., Liu, Y., 2016. Evaluation of promoting industrial symbiosis in a chemical industrial park: a case of Midong. J. Clean. Prod. 135, 995–1008.
Heck, P., 2006. Circular Economy Related International Practices and Policy Trends, Consulting Report for the World Bank Project on Policies for Promotion of a Circular Economy in China. The World Bank, Beijing (IfaS, Environmental Campus Birkenfeld).
Li, W., Zhang, T., 2005. Research on the circular economy evaluation index system in resource based city. Sci. Sci. Manag. S. T 8.
Liu, Z., Geng, Y., Park, H.-S., Dong, H., Dong, L., Fujita, T., 2016. An emergy-based hybrid method for assessing industrial symbiosis of an industrial park. J. Clean. Prod. 114, 132–140.
Ma, J., Fan, Z.P., Huang, L.H., 1999. A subjective and objective integrated approach to determine attribute weights. Eur. J. Oper. Res. 112, 397–404.
Ma, Y., Zhou, X., Zhang, X., Zhou, W., Le, Q., 2015. Necessity and main scientific problems of urban wastewater reclamation and reuse in Shanghai. Water Purif. Technol. 34, 70–72, 131.
Meng, M., Yu, D., 2004. Brief discussion on development and utilization of non-traditional water resources in Shanghai, In: The 4th International Conference on Watershed Management and Urban Water Supply, Shenzhen, China, pp. 216–221.
METI, 2004. Handbook on resource recycling legislation and 3R initiatives. In: Ministry of Economy, T.a.I (Tokyo, Japan).
Morioka, T., Tsunemi, K., Yamamoto, Y., Yabar, H., Yoshida, N., 2005. Eco-efficiency of advanced loop-closing systems for vehicles and household appliances in hyogo eco-town. J. Ind. Ecol. 9, 205–221.
National Bureau of Statistics of China, 2015. Circular Economy Development Index of China Is 137.6 in 2013. National Bureau of Statistics of China.
Pearce, D.W., Turner, R.K., 1990. Economics of Natural Resources and the Environment. Harvester Wheatsheaf, London.
Qiu, W., 2002. Management Decision and Applied Entropy. China Machine Press, Beijing.
Shaanxi Provincial Bureau of Statistics, 2015. Study on Circular Economy Assessment Indicator System in Shaanxi Province. Shaanxi Provincial Bureau of Statistics.
Shanghai Municipal Bureau of Statistics, 2015. Shanghai Statistical Yearbook. China Statistics Press, Beijing.
Su, B., Heshmati, A., Geng, Y., Yu, X.M., 2013. A review of the circular economy in China: moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227.
Urumqi Municipal Bureau of Statistics, 2015. Urumqi Statistical Yearbook. China Statistics Press, Beijing.
Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: analysis of the Eco-Town program 1997-2006. J. Environ. Manag. 90, 1544–1556.
Wei, C., 2016. Garbage Dumping Halted at Scenic Lake. ChinaDaily.
Wu, H.Q., Shi, Y., Xia, Q., Zhu, W.D., 2014. Effectiveness of the policy of circular economy in China: a DEA-based analysis for the period of 11th five-year-plan. Resour. Conserv. Recyc. 83, 163–175.
Xue, B., Chen, X.-p., Geng, Y., Guo, X.-j., Lu, C.-p., Zhang, Z.-l., Lu, C.-y., 2010. Survey of officials' awareness on circular economy development in China: based on municipal and county level. Resour. Conserv. Recyc. 54, 1296–1302.
Ye, Z., 2003. Determination of indicator normalization methods in multi-indicator comprehensive evaluation (in Chinese). Stat. Sci. Pract. 24–25.
Zeng, S., Ren, Y., Wang, W., 2009. Research of circular economy assessment: progress and prospect (in Chinese). Ecol. Environ. Sci. 28, 783–789.
Zou, Z.-H., Yun, Y., Sun, J.-N., 2006. Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. J. Environ. Sci. 18, 1020–1023.