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FULL PAPER

Match Circular Economy and Urban Sustainability: Re-investigating Circular Economy Under Sustainable Development Goals (SDGs)

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Abstract

The concept of circular economy (CE) offers an innovative and systematical approach to address a number of urban sustainability issues, via exploring symbiotic ways to design circular urban systems and optimizing the materials and energy metabolism of cities, so as to mitigate environmental footprints. Urban sustainability is highlighted as a critical issue in the Sustainable Development Goals (SDGs) proposed by United Nations; hence, in nature, circular economy could offer a number of solutions towards SDGs in urban scope. As trade-offs, circular economy also potentially causes negative impacts to business-as-usual scenario, which is easily to be ignored. To highlight this scientific issue, this paper identified and matched the role of circular economy in realizing 17 SDGs in urban scope. How circular economy strategy could potentially affect the SDGs, whether positive or negative, were comprehensively evaluated. We expect such findings could support an equilibrium decision-making on circular economy promotion in cities, rather than an optimum solution to a single target under the triple bottom line of sustainability.

Keywords Circular economy · Urban sustainability · SDGs · Life cycle sustainability assessment · Inclusive city

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Introduction

It is reported that cities will accommodate 70% of the world's population by 2050 and are already responsible for most of the global environmental footprints, in terms of carbon and resources [1–3]. Cities expand to host a growing population while the Sustainable Development Goals (SDGs) require an urgent answer on how to deal with the complex and interrelated societal-economic-environmental challenges. As a result, urban sustainability is clearly highlighted as a critical issue in realizing the SDGs [4–6]. Strengthening urban sustainability under the challenges like climate change, minimizing environmental footprints, and achieving optimal resource options are critical [7–9]. With the surging urban population (highlighted in Fig. 1), rapid growth economy, industrialization, enhanced living quality, and the underlying resources and energy consumption, even the optimistic projections of future technological solutions are unlikely to achieve the optimal optimistic environmental targets (e.g., 50% CO_2 mitigation) due to increasing demand [10–12]. Therefore, it urgently requires new and systematic solutions apart from pure technical options, to realize the target of Goal 11 of SDGs: "Sustainable cities and communities" [13–15]. Among the significant challenges related to SDGs, resource efficiency and municipal and other waste management is critical to reducing cities' environmental footprints to be more sustainable [13, 16, 17].

Circular economy (CE) provides such a systematical approach to explore symbiotic ways to design circular urban systems and optimize the materials and energy metabolism of cities to mitigate environmental footprints [14, 18–20]. In response to the CE strategy, in recent years, initiatives such as "eco-cities," "circular cities," and "zero-waste cities" have been initiated around the globe (for example, Shanghai, Tokyo, Amsterdam, San Francisco), by visionary local leaders and practitioners [3, 11, 17, 21]. In an ideal circular or zero-waste city, the places are expected to minimize waste generations via optimal waste recycling, urban industrial symbiosis, and other life cycle management measures on resource and energy circulation [7, 8, 22, 23].

Based on the circular economy strategy, many global cities have taken actions to going zero waste. While such campaigns look like these would turn our society on the way to go green, social and cultural change in cities generates more complex challenges for environmental

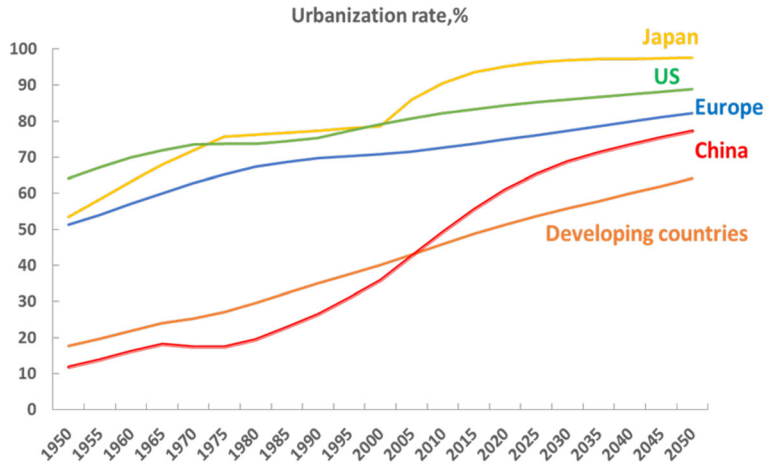

Fig. 1 Urbanization rate of various countries, 1950 to 2050

sustainability [24–26]. By changing the linear economy into a circular economy, the circular economy actually changes many other basic elements in our economic system as well [7, 27, 28]. For example, the changed urban metabolism derived from the projection of circular economy policies will result in the change of supply chain in the business model, which, inevitably, will drive some pros and cons to various economic sectors [29–32]. One of the most pressing issues presenting the negative impact of the circular economy on the urban waste sector is the immense exploitation of the majority of the members who actually are "employees" of this sector [11, 33], resulting in a social exclusion. Typical phenomenon happens in China, India, and many countries in South East Asia; external scavengers and informal collectors provide cities with cheap waste management services, but difficult to obtain legal living space, and even less in the forecasting future with zero-waste strategies [13, 34–36]. Such calls for a highlight from urban managers to pursuit a mutual benefit between social inclusiveness and environmental sustainability.

Actually, such a challenge calls for a transition of decision make art, or rather, a transition from optimal approach to equilibrium approach. The fundamental "triple bottom line" principle of sustainable development, namely "economic efficiency," "social equity," and "environmental responsibility," offers some solution [29, 37–39]. The ideology of sustainability pursues a balance between the triple bottom line, and to fulfill this target, in 2015, the United Nations (UN) proposed 17 sustainable development goals (SDGs), containing 169 sub-indicators, as a blueprint for human beings to achieve a better and more sustainable future by 2030 [16, 40–42]. Taking the social, economic, and environmental issues as a whole, SDGs provide a new system boundary for circular economy designers, to consider not only the minimization of waste generation and increment of recycling (an efficiency perspective) but also a broader impact on the social and economic system, whether positive or negative [43–46]. Therefore, it would be valuable to conduct a comprehensive analysis on how circular economy could contribute (positive) or affect (negative) the 17 SDGs, and how we could further design countermeasures and policy implications to leverage the trade-offs. So far, to our best knowledge, such comprehensive studies have been rather limited.

Based on the above highlights, this paper aims to analyze and discuss the role of circular economy in realizing 17 SDGs in urban scope. The potential benefits and trade-offs of the circular economy on the SDGs are comprehensively evaluated. We expect the findings could support an equilibrium decision-making on circular economy promotion in cities, so as to better fulfill the triple bottom line of sustainability.

The organization of this paper is as follows: after this introductory section, the "Circular Economy, Sustainable Development Goals (SDGs), and Urban Sustainability" section makes a systematic exploration on the concept of circular economy and SDGs, and analyze how they contribute to urban sustainability; the "Causal Analysis on Circular Economy and SDGs" section analyzes and match how circular economy will contribute and affect the SDGs and provides policies implications; and finally, the "Highlights and Conclusions" section concludes the main findings and highlights future concerns.

Circular Economy, Sustainable Development Goals (SDGs), and Urban Sustainability

The concept of "circular economy" seeks systematical solution to substitute the traditional linear economy, with emphasis on the concept of "circularity," and promotes "3R" principles,

namely reduce, reuse, and recycle [17, 47, 48]. It pursues an ideal economic system, in which waste is minimized and more resources could be reused and recycled in closed-loop systems [19, 30]. Under the "waste hierarchy" theory (Fig. 2), the circular economy improves the resource efficiency and economic efficiency in the whole system by promoting the 3R strategies (which was listed as the top 3 more preferable options in the waste hierarchy). To realize the 3R, technological innovations, social transitions, and business model are adopted to improve the resources/energy utilization efficiency, mitigating the lifecycle emission, creating more benefits, and enhancing the resources/energy security [26, 39, 49]. Therefore, a transition to a circular economy not only reduces the negative impacts of the linear economy. Rather, circular economy represents a systemic shift that generates business and economic opportunities, creates environmental and societal benefits, and builds long-term resilience for our economy. It is also a natural skybridge to link to the fundamental targets of SDGs.

In application into urban scope, circular economy offers a systematical approach to explore symbiotic ways, such as urban industrial symbiosis and community waste separation and recycling, to design circular urban systems and optimize the metabolism of cities, to enhance resource efficiency and reduce environmental footprints [1, 16, 22]. As Fig. 3 illustrated, by transiting into a circular urban system, material and energy flow inputs to the cities and waste generation as output are expected to be minimized.

To explore this issue in a more fundamental way, as Fig. 4 illustrated, urban sustainability could be expressed as urban resource multiplying efficiency, while the resource is limited to enhancing the efficiency of the urban system is critical. Circular economy provides a guidance to properly design the urban space, industrial facilities, and infrastructure into a closing loop. Via this way, it is expected to enhance the system resource efficiency, so as to finally support higher urban sustainability. It hereby concludes that circular economy offers an innovative pathway to forward urban sustainability transition, from a linear economy (mass production,

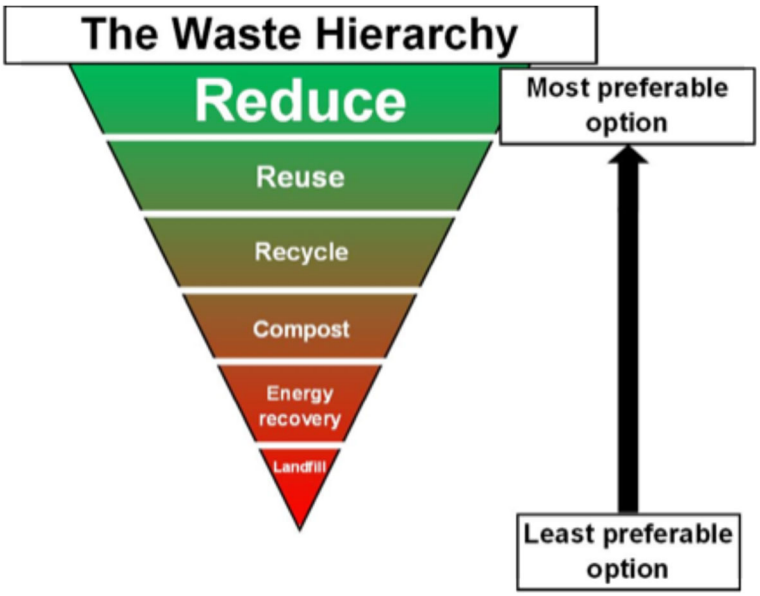

Fig. 2 3R of circular economy and waste hierarchy

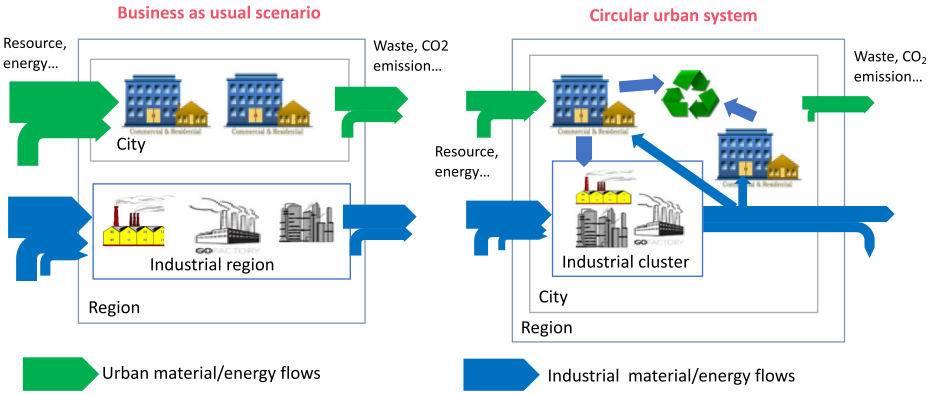

Fig. 3 Circular economy changes urban metabolism

mass consumption, and mass resource inputs) to a final stage of more ecological harmonious eco-city.

However, urban sustainability is far more than "resource efficiency" and "waste minimization." City is a hub not only of bulky resources and energy metabolism but also intensive socioeconomic activities, targeting to provide desired outputs for human beings, such as better quality of life and social equity. Therefore, urban sustainability is closely linked to SDGs in urban scope [45, 50, 51]. 17 SDGs offer guidance and complementary solutions for circular economy to better adapt to a new economic system, with consideration to both benefits and trade-offs derived from circular economy, in different aspects of sustainability.

A critical part of this topic is how we adopt an "inclusive" circular economy solution to cities. Inclusive development calls for attention to consider whether development progress is sufficiently widespread for the majority of a population to benefit [44, 52, 53]. Figure 5

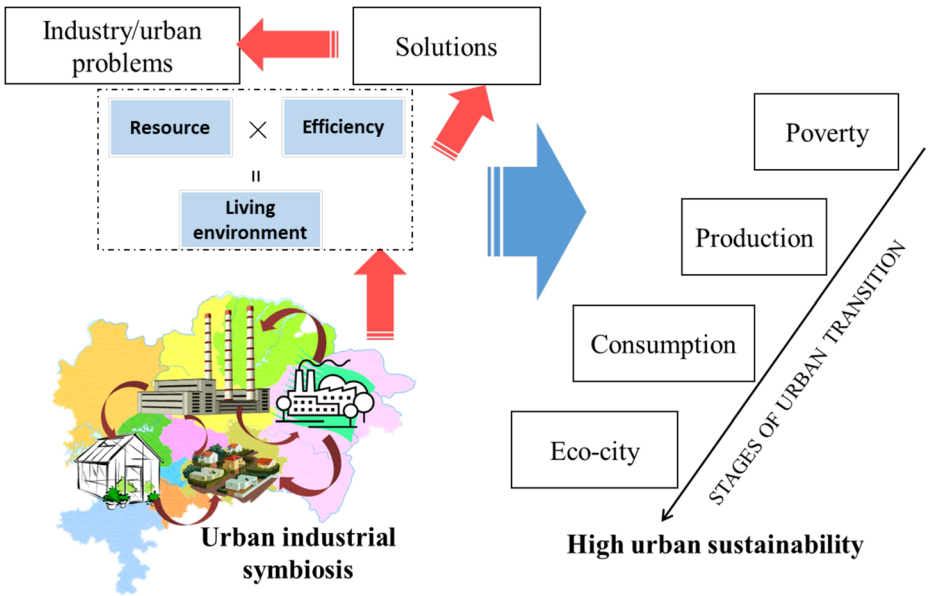

Fig. 4 Schematic chart of circular urban system contribute to urban sustainability transition

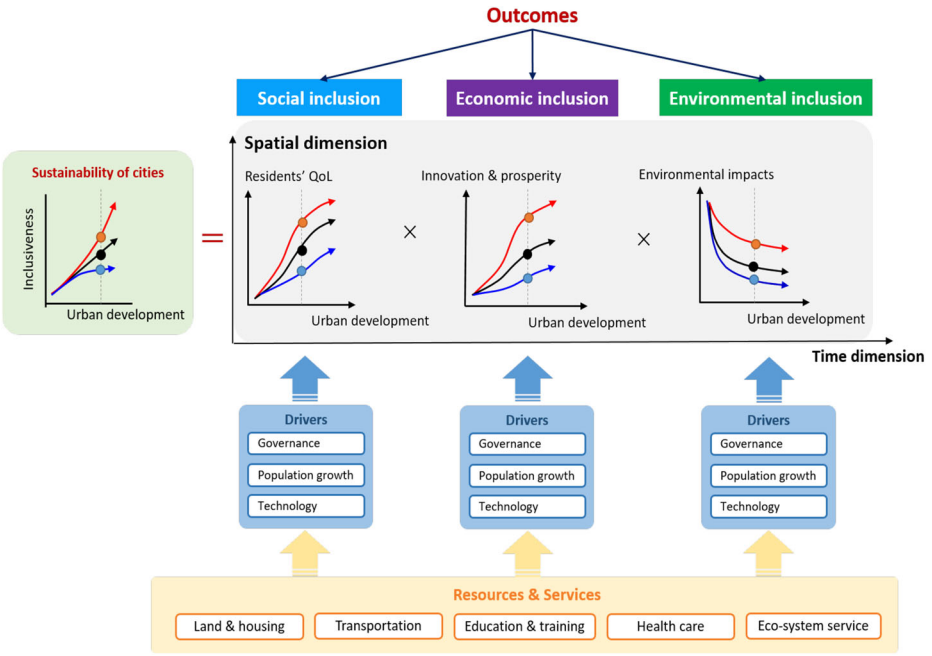

Fig. 5 Causal map of urban sustainability, inclusive development, and SDGs. Source: [5]

illustrates a causal map of urban sustainability, inclusive city, and SDGs. In an inclusive city, social, economic, and environmental inclusion is highlighted to offer a pathway to enhance the overall "urban sustainability," not an optimization on a single dimension. However, in the realistic decision-making on urban management, how the three dimensions are interlinked and mutually affected is usually neglected [54–56].

To tackle the above scientific challenges, an investigation to match and semi-quantify circular economy's contribution to 17 SDGs and related sub-indicators on an urban scale is valuable for urban managers. The follow-up section will conduct a comprehensive causal analysis via matching critical dimensions of circular economy (3R, circularity, business model, sound circular technologies, and social system) to the 17 SDGs and 169 targets for the goals. According to the mutual relationship analysis, this paper proposes an "inclusive circular economy" roadmap and policy recommendations, for a future urban sustainability transition.

Causal Analysis on Circular Economy and SDGs

Match Elements of CE to 17 SDGs

To help to provide a panoramic view on how circular economy will have impacts on SDGs and its application on urban scale, we conduct a causal analysis on the mutual relationship between key elements of circular economy and 17 SDGs. The result is presented in a heat map shown in Fig. 6. The elements of circular economy concerned in this paper, as well as the 17 SDGs, are summarized in Tables 1 and 2. The elements of circular economy are screened and selected based on literature review on the papers, complemented by experts' survey on

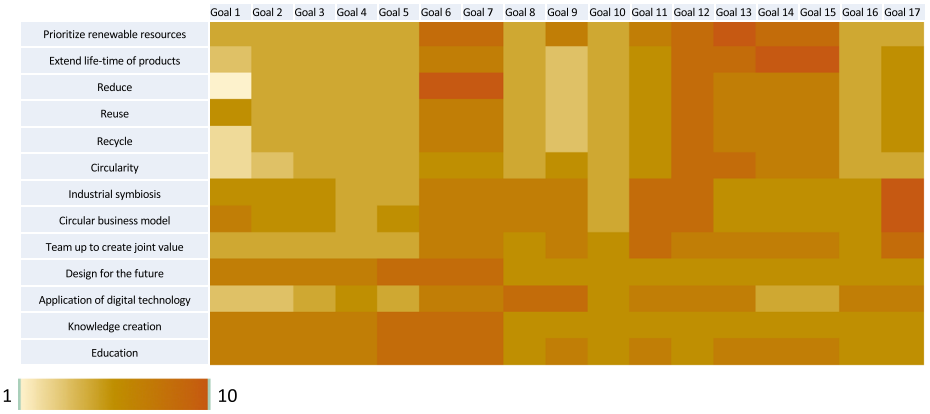

Fig. 6 A preliminary matching analysis on circular economy and SDGs

building a knowledge database for circular economy, as a part of outcomes of an EIT Raw Materials project in 2017–2018. For the semi-quantification to the mutual interlinkage, a 1–10 grade method is applied to represent from most negative to a most positive relationship.

Based on Tables 1 and 2, we semi-quantify the potential causal relationship between 13 key elements of circular to 17 SDGs, and the result is presented in Fig. 6. A general finding is that circular economy has a significant potential positive contribution to most SDGs, which, is also easily understandable. A more specific finding is by changing the current more like linear economy since the industrial revolution, circular economy changes many fundamental elements in our current economic system, and therefore, some inevitable negative effects are detected as well.

- CE-1: Prioritize renewable resources: with more utilization of renewable resources and renewable energy, significant environmental benefits in the whole life cycle are expected

Table 1 Details of SDGs

17 SDGs	Content and target	Category of TBL
Goal 1	No poverty	Economic
Goal 2	Zero hunger	Economic
Goal 3	Good health and well-being	Economic
Goal 4	Quality education	Social
Goal 5	Gender equality	Social
Goal 6	Clean water and sanitation	Environmental
Goal 7	Affordable and clean energy	Environmental
Goal 8	Decent work and economic growth	Economic
Goal 9	Industry, innovation, and infrastructure	Economic
Goal 10	Reduced inequalities	Social
Goal 11	Sustainable cities and communities	Economic and Environmental
Goal 12	Responsible consumption and production	Economic and ##
Goal 13	Climate action	Environmental
Goal 14	Life below water	Environmental
Goal 15	Life on land	Environmental
Goal 16	Peace, justice, and strong institutions	Social
Goal 17	Partnerships	Economic, social, and environmental

Source: https://sdgs.un.org/2030agenda

Table 2 Details of circular economy

Key elements	Content and target	Category of TBL
CE 1	Prioritize renewable resources	Environmental and economic
CE 2	Extend lifetime of products	Environmental
CE 3	Reduce	Environmental
CE 4	Reuse	Environmental
CE 5	Recycle	Environmental
CE 6	Circularity	Environmental and economic
CE 7	Industrial symbiosis	Environmental and economic
CE 8	Circular business model	Economic
CE 9	Team up to create joint value	Economic and social
CE 10	Design for the future	Economic, social, and environmental
CE 11	Application of digital technology	Economic and Environmental
CE 12	Knowledge creation	Economic, social, and environmental
CE 13	Education and pro-environmental behavior	Environmental and social

to be reduced, as exploration process for the natural resources is heavily polluted. By adopting this strategy, it will strongly contribute to environmental goals in SDGs (goals 6, 7, 12, 13, 14, 15), but moderate contributions to social aspects.

- CE-2: Extend the lifetime of products: by extending lifetime, we could reduce the circles of resource consumption in the whole life cycles. As a result, it will strongly contribute to environmental goals in SDGs. However, with the extension of the product's lifetime, particularly for the fast-moving consumer goods, it will generate uncertainty to the economic prosperity, or rather, some moderately negative impacts to economic goals in SDGs (goals 8, 9). Hence, it calls for circular business model innovation to compensate for this trade-off.
- CE-3: Reduce: it is the first layer of the waste hierarchy and could significantly reduce primary resource consumption and related waste generations, hence contributing a lot to the environmental goals in SDGs. However, the potential negative impact on the current economic system deserves more attention. A fundamental argument is the mitigation of waste in the whole system which will result in a shrink in the waste collection and recycling market, in which there are actually many employments existing (and many s in the format of informal economy where poor people engaged). Therefore, reduce as the first priority in the "3R" strategy of circular economy, has potential negative impact on some economic and social goals in SDGs (goals 1, 2, 9, 16). Such trade-off could be leveraged if a proper circular business model and social compensation policies could be adopted.
- CE-4: Reuse, the second layer of the waste hierarchy: Apart from contributing to environmental goals in SDGs, reuse also helps to generate a new market for waste collection, recycling, and remanufacturing, hence contributing to economic and social goals as well. We hereby identify a positive contribution to goals 1, 11, 12, and 17 in social and economic dimension.
- CE-5: Recycle: similarly, recycle activities stipulate new market for waste collection, recycling, and remanufacturing, hence contributing to economic and social goals in SDGs.
- CE-6: Circularity: it is a key indicator representing the extent of circular economy application. Higher circularity drives to higher ratio recycling and results in more reuse and resource mitigation. Therefore, it contributes positively to the environmental goals of SDGs. Similar to reuse and recycle, due to the change of the current economic system,

potential negative impacts are identified to certain social and economic goals, for example, no poverty- and justice-related goals.

- CE-7: Industrial symbiosis refers to the collaboration among companies in certain geographical proximity, via exchanging materials and wastes. It is environmental innovation as well as business innovation to drive the development of circular economy and could contribute to the triple bottom line of sustainability by innovating the whole supply chain. Therefore, we identify industrial symbiosis that will strongly contribute to SDGs 9 and 12, apart from typical environmental goals (6, 7, 13, 14, 15).
- CE-8: Circular business model: circular business model generates new market opportunities for reuse and recycle activities, therefore reducing the negative of the circular economy on economic and social system.
- CE-9: Teaming up to create joint value could positively contribute to all SDGs but the effects are difficult to be quantified and implemented.
- CE-10: Design for the future could reduce the accumulative cost for companies and society from a life cycle perspective. A typical case is eco-design on product and supply chain. With changing the product's shape, materials, and function, the down-stream resource consumption, waste emissions, and waste treatment costs could be mitigated a lot as well. Therefore, we identify that apart from environmental goals, design for the future could strongly contribute to the social and economic dimensions of SDGs as well.
- CE-11: Application of digital technology could help to build a circular business model (for example, new business to consumer or consumer to consumer model, which could reduce the consumptions and emissions on the supply chain). Digital technologies could also enhance the production efficiency of products. One point that deserves attention is that digital technologies could potentially increase resource consumption and emissions by increase the "rebound effect"; therefore, social awareness building is important.
- CE-12: Knowledge creation will positively contribute to all SDGs but takes a longer time to realize the benefits.
- CE-13: Education and pro-environmental behavior will also provide a fundamental element to realize the SDGs, and by combining technologies innovation, design for the future, and knowledge creation will lay the foundation for social transition.

Recommendations and Implications in Mega City

According to the matching analysis between circular economy strategy and SDGs, on the one hand, we acknowledge the contributions from circular economy to most SDGs; on the other hand, we should also pay attention to leverage the trade-offs, by better systemic innovation. This paper hereby highlights several critical implications on an urban scale, to forward the urban sustainability.

- A comprehensive decision-making support tools helps to analyze the triple bottom line in the circular economy innovation: before tackling the potential negative effects of the circular economy on SDGs, useful information disclosure via the advanced analytical tool is important. Particularly, semi-quantified social dimensional information and hidden effect from a life cycle perspective are usually ignored by managers and decision-makers. This paper hereby calls for the development on a comprehensive evaluation tool that could offer information on social-economic and environmental evidence of how circular

economy could affect the SDGs in a life cycle perspective. The current prevailing life cycle sustainability assessment is helpful, but social impacts, evidence in long-term scenarios, and micro-information (for example, the individual behaviors) are still needed to be improved in the future. To support this, integration with some macroeconomic model like the computable equilibrium model (CGE model) and agent-based model (ABM) will be rather helpful.

- Promotion of industrial symbiosis, and urban industrial symbiosis as not only environmental innovation but also business and social innovation to forward the circular economy, is illustrated in Fig. 7. By promoting industrial symbiosis, we change the linear economic system as business-as-usual scenario, into a circular system via exchange of wastes as raw materials. It not only realizes the waste minimization (as industrial symbiosis tries to use wastes as materials), waste and resource reuse (exchange between companies), and recycle, which are the top three options in the waste hierarchy, but also builds a new business model. When exchanging wastes into materials, the previous wastes with low or even minute market value (because companies pay to waste treatment) become resources with higher market value, hereby offering great motivation to company and individuals to practice circular economy. An environmental innovation hereby transits into business innovation and will contribute social benefits (e.g., new jobs created in the business model). As a result, industrial symbiosis, which is identified as a critical element of the circular economy, is a good example to generate triple bottom line credits to SDGs.
- For circular business model development to shift "gray jobs" into "green jobs," illustrated in Fig. 8, one trade-off of the circular economy is that it will break down some of the current economic system, which, as we identify in the last section, generates a negative impact on social dimension. A typical case is the "gray jobs" engaged in urban informal waste sector. The promotion of the circular economy will certainly reduce such employment opportunities and cause a negative impact on economic and social dimensions of SDGs (e.g., goals 1, 2, 3, and 8). However, on the other hand, if we could create proper circular business model innovation, as the left side of Fig. 8, they will offset the job loss in traditional economic sectors and generate even more employment opportunities, hence increasing the social benefits in the whole life cycles.

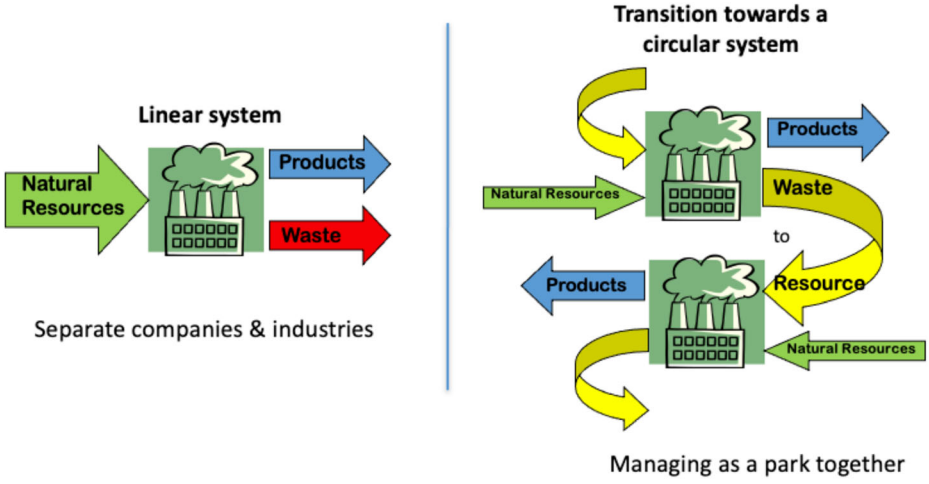

Fig. 7 Innovation as urban and industrial symbiosis

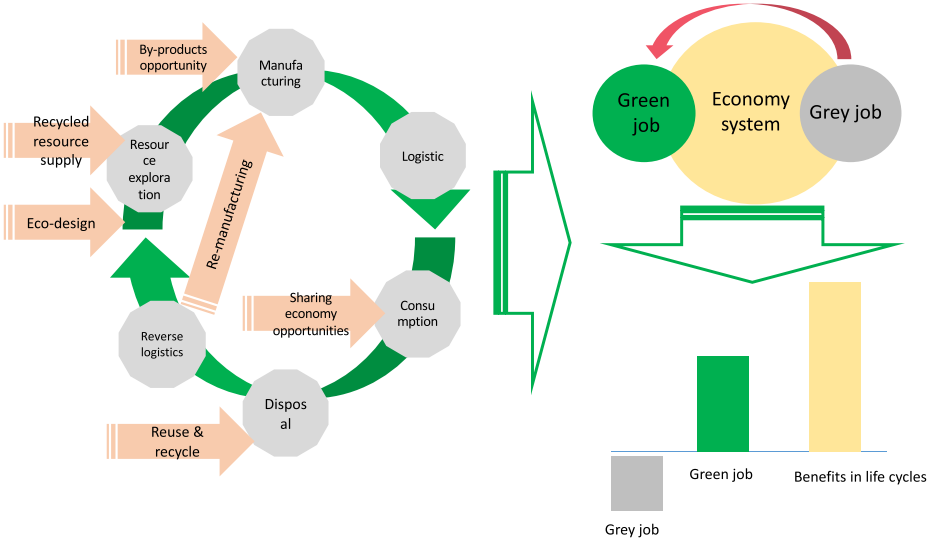

Fig. 8 Circular business model could forward "gray" to "green" jobs shift

Highlights and Conclusions

Circular economy is always described as a fantastic fairy tale that could resolve the environmental crisis. However, by matching the key elements of circular economy and 17 SDGs, this paper highlights that many trade-offs should not be ignored and proper countermeasures could be enhanced to tackle this challenge. Based on a literature review and keyword scanning, we identified and matched the role of circular economy in realizing 17 SDGs in urban scope. The potential impacts of circular economy on the SDGs, whether positive or negative, were comprehensively evaluated and identified. On the one hand, circular economy has a significant potential positive contribution on most SDGs. On the other hand, by changing the current linear economy into circular system, circular economy changes many fundamental elements in our current economic system, and therefore, some inevitable negative effects were detected as well, mainly in social and economic SDGs.

As countermeasures, advanced analytical tool integrating with macroeconomic model social behavior simulation model, industrial symbiosis, which not only change the perception to industries but also plays a role as social and business model innovation, as well as an innovative circular business model to transform affected "gray job" into "green job," is highly recommended to urban managers and policy-makers. We expect such findings could support an equilibrium decision-making on circular economy promotion in cities, rather than an optimum solution to single target under the triple bottom line of sustainability.

This paper is not submitted to more than one journal for simultaneous consideration. This paper is original and has not been published elsewhere in any form or language. Reuse of material (one figure) is clearly marked with reference. This paper does not involve the single study split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. This paper does not involve concurrent or secondary publication. The results of this paper are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors of this paper adhere

to discipline-specific rules for acquiring, selecting, and processing data. No data, text, or theories by others are presented as if they were the author's own. Proper acknowledgments to other works are given.

Abbreviations *SDG,* Sustainable Development Goal; *CE,* Circular economy; *TBL,* Triple bottom line; *3R,* Reduce, reuse, and recycle

Author's contribution L.D. conceived of the idea of the research, made the structure, supervised this research work, and provided guidance. Z.L. and Y.B. conducted the data collection and wrote the text. All authors contributed significantly to this work by reading and editing.

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Code availability Not applicable.

Declarations

Ethics approval This research does not include human participants, their data, or biological material.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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