

An Integrative Review of Monitoring and Evaluation of Urban Circularity in Developing Countries*

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Abstract: As centers of economic activity, cities face pressures from population growth, resource depletion, and pollution. The Circular Economy (CE) provides a greener alternative to the traditional model, facilitating the achievement of the Sustainable Development Goals (SDGs). However, blindly pursuing circularity may undermine long-term sustainability. Compared to advanced economies, the CE remains sparsely implemented in emerging economies. There is still controversy surrounding the relationship between urban CE and sustainability. This study analysed the CE principles adopted in developing countries, aiming to monitor and assess the consistency between urban circularity and the SDGs. The findings suggest that the number of CE principles mentioned in definitions has increased over time. Environmental indicators closely align with various SDGs, while economic indicators are linked to SDGs 8 and 9, and social indicators to SDGs 2 and 3. Furthermore, the study notes that digital technologies have great potential to improve efficiency and advocates a multi-dimensional approach. The novelty of the research lies in deepening the insight of urban circularity, identifying linkages between indicators and SDGs in emerging economies, and spotlighting the key role of digital technologies.

Keywords: Urban Circular Economy (CE); Sustainable Development Goals (SDGs); Circularity; Monitoring; Evaluation.

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發展中國家城市循環性監測與評估的綜合回顧

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摘要：城市作為經濟活動的中心，面臨著人口增長、資源枯竭和污染帶來的壓力。迴圈經濟為傳統模式提供一種更綠色的替代方案，有助於實現可持續發展目標。然而，盲目追求迴圈性可能損害長期可持續性。與發達經濟體相比，新興經濟體的迴圈經濟實施仍然較少。關於城市迴圈經濟與可持續性之間的關係仍存在爭議。本研究分析發展中國家所採用的迴圈經濟原則，旨在監測和評估城市迴圈性與可持續發展目標的一致性。研究結果表明，隨著時間推移，定義中提及的迴圈經濟原則數量有所增加。環境指標與多項可持續發展目標高度契合，經濟指標與可持續發展目標第八項和第九項相關，社會指標則與第二項和第三項相關。此外，研究指出，數字技術在提高效率方面具有巨大潛力，並宣導採用多維度的方法。本研究的創新之處在於深化對城市迴圈性的理解，識別新興經濟體中各項指標與可持續發展目標之間的聯繫，並突出數字技術的關鍵作用。

關鍵詞：城市迴圈經濟、可持續發展目標、迴圈性、監測、評估

1. Introduction

Circular economy (CE), recognised as a model for eco-friendly economics which promotes the coordination of economic improvement and environmental protection, has received extensive attention. In 1989, Pearce and Turner originally introduced the notion of ‘circularity’ to examine the interrelatedness between environmental and economic domains.¹ In 2016, Ghisellini proposed that in a closed system, always exists a state of equilibrium between the resources consumed and the waste generated.² The theory of CE represents a contrasting solution to the linear (acquisition-manufacturing-disposal) economy.³ The CE's core principle involves decarbonizing economic activities and minimizing environmental impacts. Dwivedi et al. have recognised the urgency of the shift towards a CE model and the potential for sustainable development.⁴ Over the past few years, some scholars have also explored how CE performance contributes to the SDGs.⁵ Although Kara has examined micro-level contributions to the SDGs,⁶ the link between CE principles and SDGs at the city level still remains to be further explored. Over recent years, the principles of CE have evolved to further expand from the 3Rs principles to the 10Rs principles,⁷ and the urban CE requires adjusting to the connotative demands of CE in the

¹ Pearce, D. W., & Turner, R. K. *Economics of Natural Resources and the Environment*, Johns Hopkins University Press, 1989.

² Ghisellini, P., Cialani, C., & Ulgiati, S., “A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems,” *Journal of Cleaner Production* 114.5 (2016): 11-32.

³ Bocken NM, De Pauw I, Bakker C, Van Der Grinten B., “Product Design and Business Model Strategies for a Circular Economy,” *Journal of Industrial and Production Engineering* 33.5 (2016): 308-20.

⁴ Dwivedi, A., Chowdhury, P., Paul, S. K., & Agrawal, D., “Sustaining Circular Economy Practices in Supply Chains during a Global Disruption,” *The International Journal of Logistics Management* 34.3 (2023): 644-673.

⁵ Panchal, R., Singh, A., & Diwan, H. “Does Circular Economy Performance Lead to Sustainable Development? —A Systematic Literature Review,” *Journal of Environmental Management* 293.17 (2021): 112811.

⁶ Tezyapar Kara, I., Kremser, K., Wagland, S. T., & Coulon, F., “Bioleaching Metal-bearing Wastes and By-products for Resource Recovery: A Review,” *Environmental Chemistry Letters*, 21.6 (2023): 3329-3350.

⁷ Reike, D., Vermeulen, W. J., & Witjes, S., “The Circular Economy: New or Refurbished as CE 3.0?—Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History

new era. Simultaneously, the increase in urban CE does not necessarily attain urban sustainability.⁸ The blind pursuit of urban circularity can easily succumb to the temptation of circularity for the purpose of circularity.⁹ The complex transition to CE requires a comprehensive evaluation of urban circularity, including definitions, indicators, and evaluation methods. Furthermore, while developed countries are intensifying the implementation of circular principles across various sectors, developing countries encounter skepticism regarding the sustainability and CE agenda due to constraints such as a lack of funding and public awareness. In this connection, it is imperative to comprehensively monitor and assess the urban circularity and sustainability in developing countries.

Current scientific research has several limitations. First, the concept of the urban CE is ambiguous. Many scholars have studied the consensus notion of the CE, but the notion itself remains controversial.¹⁰ The theory of CE is fundamentally connected to its core principles.¹¹ Nevertheless, further clarification on how the urban CE definition aligns with the essential principles of the CE is needed to improve our understanding of its application. Secondly, there is an absence of a thorough evaluation system of urban circularity to examine the contribution to the SDGs.¹² Saidani has argued that there is a ‘mismatch’ between the evaluation tool and the criteria for evaluating circular practices and sustainable

and Resource Value Retention Options,” *Resources, Conservation and Recycling* 135.8 (2018): 246-264.

⁸ Cortés, A., Esteve-Llorens, X., González-García, S., Moreira, M. T., & Feijoo, G., “Multi-product Strategy to Enhance the Environmental Profile of the Canning Industry towards Circular Economy,” *Science of The Total Environment* 791.42 (2021), 148249.

⁹ Harris, S., Martin, M., & Diener, D., “Circularity for Circularity’s Sake? Scoping Review of Assessment Methods for Environmental Performance in the Circular Economy,” *Sustainable Production and Consumption* 26.2 (2021): 172-186.

¹⁰ Kirchherr, J., Yang, N. H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K., “Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions,” *Resources, Conservation and Recycling* 194.7 (2023): 107001.

¹¹ Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C. A., & Jung, N., “Towards Circular Cities-Conceptualizing Core Aspects,” *Sustainable Cities and Society* 59.8 (2020): 102143.

¹² Shevchenko, T., Esfandabadi, Z. S., Ranjbari, M., Saidani, M., Mesa, J., Shevchenko, S., Yannou, B., & Cluzel, F., “Metrics in the Circular Economy: An Inclusive Research Landscape of the Thematic Trends and Future Research Agenda,” *Ecological Indicators* 165 (2024): 112182.

development.¹³ Furthermore, there exists a notable focus on environmental and economic aspects, which often overshadows the social dimension.¹⁴ Moreover, many scholars have monitored the circularity of cities in developed countries,¹⁵ while there is less monitoring and evaluation in developing countries. Third, current studies may not adequately consider the contribution of novel technologies to monitoring and evaluating the CE of cities in developing countries. With the development of technologies such as the Internet of Things (IoT), big data analytics, artificial intelligence (AI), and blockchain, increasing numbers of studies have initiated investigations into how these technologies can contribute to the application and monitoring of the CE.¹⁶ Despite the recognized potential of technologies for monitoring and evaluating the CE, it is still not clear what role these emerging technologies will be in assessing the CE in cities of developing countries. In view of these limitations, the research will tackle the following issues:

RQ1: To what extent are cities of developing countries currently implementing CE principles?

RQ2: What are the connections between the SDGs and urban CE in developing countries?

RQ3: What monitoring indicators and tools exist to assess progress towards an urban CE in developing countries, and are they appropriate and effective?

RQ4: What role do digital technologies play in monitoring and evaluating the urban CE in developing countries, and how do they promote the attainment of SDGs?

This research intends to examine and interpret definitions, indicators and methods for monitoring and evaluating the urban CE in developing countries towards the execution of

¹³ Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A., "A Taxonomy of Circular Economy Indicators," *Journal of Cleaner Production* 207.2 (2019): 542-559.

¹⁴ Mies, A., & Gold, S., "Mapping the Social Dimension of the Circular Economy," *Journal of Cleaner Production* 321.44 (2021): 128960.

¹⁵ Kopp, M., Petit-Boix, A., & Leipold, S., "Municipal Circular Economy Indicators: Do They Measure the Cities' Environmental Ambitions?," *Sustainable Production and Consumption* 50.7(2025): 431-444.

¹⁶ Chauhan, C., Parida, V., & Dhir, A., "Linking Circular Economy and Digitalisation Technologies: A Systematic Literature Review of Past Achievements and Future Promises," *Technological Forecasting and Social Change* 177.4 (2022): 121508.

the CE principles and the SDGs by conducting a review. Our goal is to provide an integrated perspective to assess the current research, existing challenges and future trends.

The innovative aspects of this research compared to other previous research efforts in this area are demonstrated by the following: Firstly, by adopting the 10Rs principles as a new framework for urban circularity evaluation, this paper deepens the conceptual understanding of urban circularity. Secondly, this study analyses how urban CE indicators in developing countries measure CE principles with direct links to the SDGs, and reveals the links between city-level environmental, economic, and social indicators and the SDGs in developing countries. Thirdly, this study conducted a comprehensive evaluation of existing methods in developing countries to understand the advantages and disadvantages of each existing methodology, concentrating on clarifying the role of digital technology tools. Fourthly, based on the findings, directions for future research are proposed.

The subsequent sections are organized as follows: Section 2 clarifies the method used to select and evaluate the literature; Section 3 demonstrates the results; Section 4 discusses the key findings and constraints, and provides a perspective on upcoming studies. Section 5 summarises the conclusions.

2. Methods

The research employed an integrative review methodology to supply a deepening comprehension of the urban CE, examining definitions, indicators, and methods. Quantitative analysis of publications encompasses detailed facts, including authorship, article titles, publication dates, geographical scope, and methodological frameworks. This was followed by a manual content analysis. This approach greatly enhances the comprehensiveness of the examination of the literature.

2.1 Retrieval Scope and Procedure

The research follows the PRISMA framework for literature search and screening. The literature selection methodology is outlined in Figure 1. This search included entries from the Scopus and Web of Science databases, focusing on articles relevant to our study from inception to 2024.

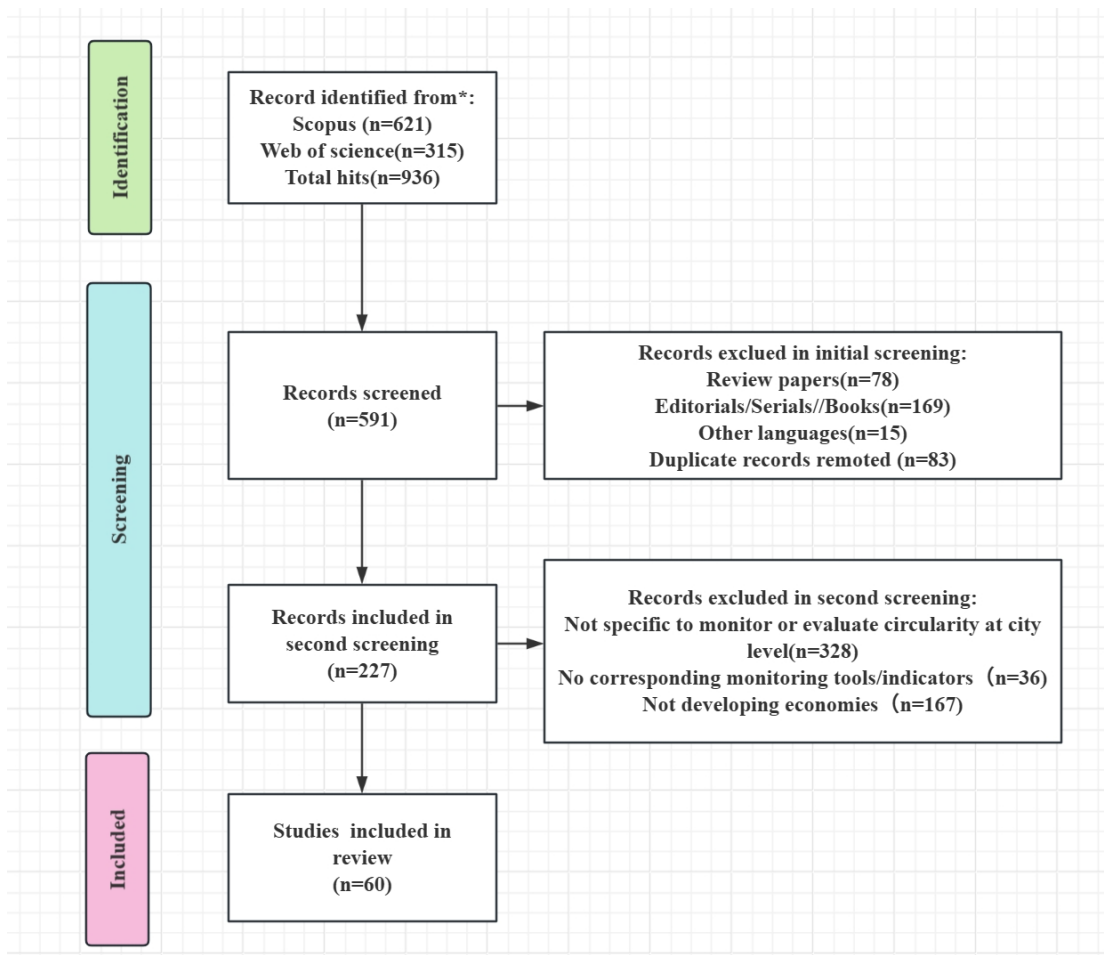


Figure 1. PRISMA Flow Diagram of Eligible Studies

Firstly, Boolean logic using the operators (AND/OR) was applied to search for terms such as ‘urban circular economy’ integrated with ‘monitoring’, ‘evaluation’, or ‘assessment’ in the title, abstract, and keywords. This initial search yielded 621 results. Then, a targeted

search in the Web of Science database using the same thematic search criteria of ‘urban circular economy’ AND (‘monitoring’ OR ‘evaluation’ OR ‘assessment’) was conducted. At the same time, the search was extended to include the keywords ‘circular economy’ and ‘city’, which yielded an additional 315 entries. Finally, a comprehensive search strategy yielded a total of 936 results.

Secondly, an initial screening process was carried out. Conference papers, book chapters, editorials (n=169), and commentaries (n=78) were excluded. Non-English language papers (n=15) and duplicate entries found in both databases (n=15) were also excluded. This refinement process resulted in a total of 591 English-language journal articles.

Thirdly, the second round of screening was conducted to identify articles that were aligned with the research theme. Initially, articles that did not encompass the urban level and circularity within their subject matter (n=328) are excluded. Subsequently, we further eliminated articles that lacked monitoring or evaluative tools or indicators (n=36). Ultimately, studies not conducted in developing countries were excluded (n=167). Consequently, this resulted in a selection of 60 articles.

2.2 Coding framework

2.2.1 Definition coding

The development of a clear definition for the urban CE required a systematic framework, which utilised the academic contributions of Kirchherr, Reike, and Hekkert.¹⁷ Among the selected articles, there are a total of 30 related to the concept of urban CE. In Appendix Table A1, a detailed overview of the definitions related to CE is provided. Although these definitions exhibit linguistic variability, they share an underlying congruence in meaning. Consequently, a meticulous process of manual coding to distill a definition that captures the universal essence of urban circular economies was conducted.

¹⁷ Kirchherr, J., Reike, D., & Hekkert, M., “Conceptualizing the Circular Economy: An Analysis of 114 Definitions,” *Resources, Conservation and Recycling* 127.12 (2017): 221-232.

To better define the notion of urban CE, the research integrates the 10Rs principles as a foundational guide for the practical application of urban CE. The 10Rs framework is demonstrated in Table 1.

Table 1. Principles of CE

R-principles	Description	Source
3Rs	Reduce, Reuse, Recycle	Lieder and Rashid (2016) ¹⁸
4Rs	Reduce, Reuse, Recycle, Recover	Kirchherr et al. (2017) ¹⁹
5Rs	Rethink, Reduce, Reuse, Recycle, Repair	Wenbo (2011) ²⁰
6Rs	Reduce, Reuse, Recycle, Recover, Remanufacture, Redesign	Yan and Feng (2014) ²¹
7Rs	Reduce, Reuse, Recycle, Recover, Rethink, Resilient, Regulate	Xing et al. (2017) ²²
8Rs	Rethink, Redesign, Reduce, Reuse, Return, Repair, Recycle/Recovery, Refuse	Maia et al. (2019) ²³
9Rs	Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover	Van Buren et al. (2016) ²⁴
10Rs	Refuse, Rethink, Reduce, Reuse, Repair,	Potting et al. (2017) ²⁵

¹⁸ Lieder, M., & Rashid, A., "Towards Circular Economy Implementation: A Comprehensive Review in Context of Manufacturing Industry," *Journal of Cleaner Production*, 115.6 (2016): 36-51.

¹⁹ Kirchherr, J., Reike, D., & Hekkert, M., "Conceptualizing the Circular Economy: An Analysis of 114 Definitions," *Resources, Conservation and Recycling* 127.12 (2017): 221-232.

²⁰ Wenbo, L., "Comprehensive Evaluation Research on Circular Economic Performance of Eco-industrial Parks," *Energy Procedia* 5.3 (2011): 1682-1688.

²¹ Yan, J., & Feng, C., "Sustainable Design-oriented Product Modularity Combined with 6R Concept: A Case Study of Rotor Laboratory Bench," *Clean Technologies and Environmental Policy* 16.1 (2014): 95-109.

²² Xing, J., Silva, J. M. V. B., & Almeida, I., "A New Conceptual Perspective on Circular Economy: Preliminary Confirmation of the 7R Principle by a Descriptive Case Study in Eastern China," *A New Conceptual Perspective on Circular Economy: Preliminarily Confirmation of the 7R Principle by a Descriptive Case Study in Eastern China*, 2017.

²³ Maia, L. C., Alves, A. C., & Leão, C. P., "Implementing Lean Production to Promote Textile and Clothing Industry Sustainability," *Lean Engineering for Global Development* (2019): 319-343.

²⁴ Van Buren, N., Demmers, M., Van der Heijden, R., & Witlox, F., "Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments," *Sustainability* 8.7 (2016): 647.

²⁵ Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A., "Circular Economy: Measuring Innovation in

	Refurbish, Remanufacture, Repurpose, Recycle, Recover	
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2.2.2 Indicator coding

Indicators are integral components that make up specific concepts, and they are used to assess urban circularity in developing countries. These indicators must satisfy a set of criteria, including validity, reliability, and utility. Validity denotes the level at which an indicator actually captures the progress of urban CE. Reliability focuses on the dependability and stability of the results. Utility refers to the practical applicability of the indicator. Furthermore, as this paper examines the relationship between urban CE and the SDGs, the relevant indicators should also be coded for their alignment with the SDGs and CE principles. Initially, a total of 98 indicators from the literature were amassed. Subsequently, duplicate indicators were eliminated to ensure that each indicator appears only once. Then, these indicators were manually coded according to the principles of the CE and the 102 indicators of the SDGs.²⁶ The selection criteria included: (i) alignment with the 10Rs framework of the CE, ensuring core principles such as reducing, reusing, and recycling; (ii) direct linkage to the SDGs, especially those related to environmental sustainability, economic growth, and social well-being; (iii) accuracy in measuring progress towards urban circularity and consistency across studies; and (iv) considering data availability and ease of measurement. Indicators not meeting these criteria were excluded. This rigorous selection process resulted in a final list of 27 indicators, which are crucial for assessing and advancing towards CE principles and the fulfillment of the SDGs.

Following the methodology of Gracia-de-Rentería et al. (2023),²⁷ this study categorised them according to their respective dimensions. Table 2 describes the SDGs selected according to the proposed approach. The economic aspect comprises SDGs 7, 8,

the Product Chain,” *Planbureau Voor De Leefomgeving* 2544 (2017).

²⁶ Sustainable Development in the European Union., “Monitoring Report on Progress towards the SDGs in an EU Context,” (2022).

²⁷ Gracia-de-Rentería, P., Ferrer-Pérez, H., & Drabik, D., “Sustainable Development Goals in the European Union and Its Regions: Are We Moving Forward in Economic, Social, and Environmental Dimensions?,” *Sustainable Development* 31.5 (2023): 3540-3552.

9, 11, and 12. The environmental aspect includes SDGs 6, 7, 11, 12, 13, 14, and 15. The social dimension includes SDGs 1, 2, 3, 4, 5, and 10. In particular, SDGs 16 and 17 do not fall strictly within the economic, environmental, or social aspects as defined in the research.

Table 2. Sustainable Development Goals

Number	Sustainable Development Goal	Dimension
SDG 1	No Poverty	Social
SDG 2	Zero Hunger	Social
SDG 3	Good Health and Well-being	Social
SDG 4	Quality Education	Social
SDG 5	Gender Equality	Social
SDG 6	Clean Water and Sanitation	Environment
SDG 7	Affordable and Clean Energy	Economic and Environment
SDG 8	Decent Work and Economic Growth	Economic
SDG 9	Industry, Innovation, and Infrastructure	Economic
SDG 10	Reduced Inequalities	Social
SDG 11	Sustainable Cities and Communities	Economic and Environment
SDG 12	Responsible Consumption and Production	Economic and Environment
SDG 13	Climate Action	Environment
SDG 14	Life Below Water	Environment
SDG 15	Life on Land	Environment
SDG 16	Peace, Justice, and Strong Institutions	/
SDG 17	Partnerships for the Goals	/

2.3 Validation Criteria for Research Questions

To ensure the rigor of this study, specific validation criteria have been delineated for each research question:

(i) **RQ1 (Assessment of Implementation Extent):** Through systematic literature review and data analysis, the current status and trends of the implementation of CE principles in cities of developing countries are clearly demonstrated. This includes the evolution of urban CE definitions, the breadth and depth of implementation.

(ii) **RQ2 (Establishment of Relationships):** By means of systematic literature review and data analysis, the specific connections between urban CE principles and the SDGs are explicitly revealed. This involves identifying and analyzing the links between urban CE indicators and the SDGs.

(iii) **RQ3 (Evaluation of Tool Effectiveness):** The effectiveness of various assessment tools in practical applications is demonstrated through the analysis of their connections with the environmental, economic, and social aspects of the SDGs.

(iv) **RQ4 (Validation of Technology-Enabled Pathways):** The practical application effects of digital technologies in the urban CE are proven through technology assessment cases.

3. Results

3.1 Article Feature Analysis

Table 3 summarises the main characteristics of the studies evaluated. The analysis of the 60 selected publications shows that from 2014 to August 2024, CE research at the city level in emerging economies has generally shown an upward trend in volume. In addition, China, India, and Brazil are emerging as the leading research development countries, with waste management, construction, and industry leading the research sectors. Among the 60 papers in our sample, 31 are from China, leading to an imbalance. This is mainly due to China's high number of publications in this field, reflecting its active research.

Table 3. Features of the reviewed studies

Feature	Categories
Year of publication	Published between 2014-2016(3), 2017-2019(9), 2020-2022(20) and 2023-2024(27).
Geography	Regions in China (31), India (5), Brazil (4), Vietnam (2), Bolivia (2), Iran (2), Egypt (1), Malaysia (1), Peru (1), Argentina (1), Cambodia (1), Pakistan (1), Serbia (1), Sri Lanka (1), Latin America (1), Zimbabwe (1), Mexico (1), Multiple countries (3).
Sector	Waste management (24), Construction (10), Industry (5), Water management (3), Mining (2), Iron and Steel (1), Energy (1), Plastic management (1), Logistics (1), Manufacturing (1) and No Specific (11).

3.2 Analysis of thematic content

The thematic investigation of the research is divided into three phases: (i) the definition of the urban CE; (ii) the indicators for monitoring and evaluating the urban CE; and (iii) the methods for monitoring and evaluating the urban CE.

3.2.1 Definition of the urban CE

Since its emergence in the 1990s, the notion of CE has transformed the linear ‘acquire-manufacture-dispose’ model into a ‘closed-loop’ framework. Ghisellini et al. propose that this system prioritises waste reduction and resource sustainability.²⁸ CE is an economic system that transcends the conventional ‘end-of-life’ approach, including strategies of reduce, reuse, recycling, and material recovery.²⁹ This system operates across various scales, from the micro-level, which concerns commodities, enterprises, and clients, to the meso-level within eco-efficient industrial parks, and up to the macro-level, encompassing urban, regional, and national domains. The primary goal aims to advance sustainability that incorporates environmental sustainability, economic growth, and social equality.

From the mid-2000s to the beginning of the 2010s, an obvious upsurge in focus on urban CE was discovered. This shift was particularly highlighted by the introduction of China's CE Promotion Law in 2008, which represented a critical legislative landmark in the urban CE. Referring to Kirchherr et al.,³⁰ the urban CE denotes the city-scale deployment of cyclic principles. Prendeville et al. depicted urban CE, which collaborates with diverse stakeholders to achieve resource loop closure, integrating CE principles within its urban development vision.³¹ Petit-Boix and Leipold expanded on this notion,

²⁸ Ghisellini, P., Cialani, C., & Ulgiati, S., “A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems,” *Journal of Cleaner Production* 114.5 (2016): 11-32.

²⁹ Kirchherr, J., Reike, D., & Hekkert, M., “Conceptualizing the Circular Economy: An Analysis of 114 Definitions,” *Resources, Conservation and Recycling* 127.12 (2017): 221-232.

³⁰ Kirchherr, J., Reike, D., & Hekkert, M., “Conceptualizing the Circular Economy: An Analysis of 114 Definitions,” 221-232.

³¹ Prendeville, S., Cherim, E., & Bocken, N., “Circular Cities: Mapping Six Cities in Transition,” *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

characterizing a circular city as one that employs the 10Rs framework across various sectors.³² Paiho et al. clarified a city implementing CE as one that, after optimising savings, efficiency, resource sharing, servitisation, and virtualisation, satisfies its residual material and energy demands through renewable resources, aiming to minimise and prolong the resource cycle.³³

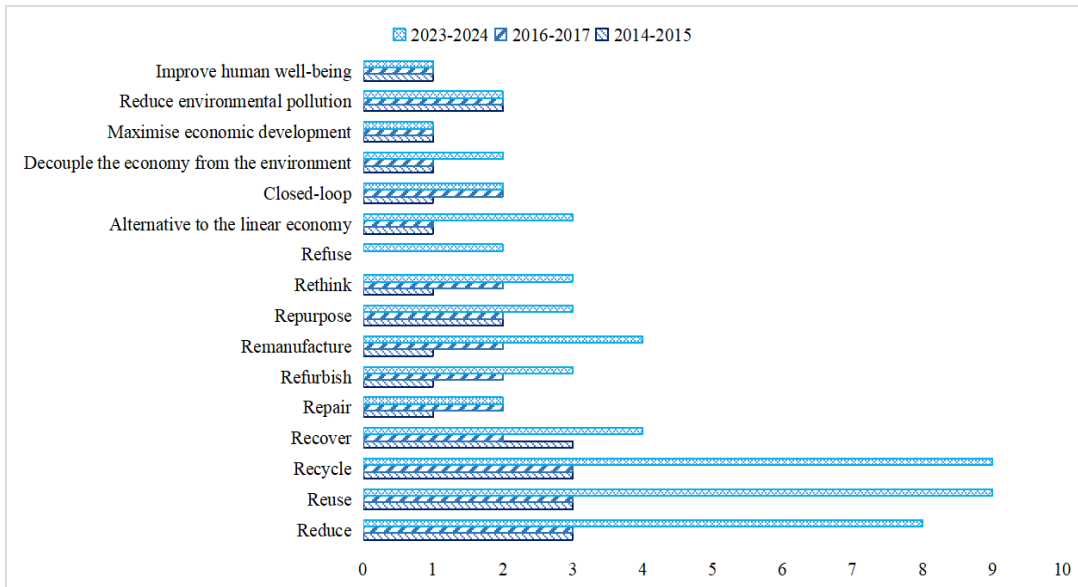


Figure 2. The codification of the core principles of the CE

Figure 2 illustrates the execution of CE principles within the definition of urban CE in developing countries. Before 2017, the employment of the 3Rs (Reduce, Reuse, and Recycle) framework in developing countries was not significant, and the application of other principles also increased relatively little. Over time, the number of CE principles mentioned has increased. The principles of urban CE have evolved from the 3Rs to a

³² Petit-Boix, A., & Leipold, S., "Circular Economy in Cities: Reviewing How Environmental Research Aligns with Local Practices," *Journal of Cleaner Production* 195.26 (2018): 1270-1281.

³³ Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C. A., & Jung, N., "Towards Circular Cities—Conceptualizing Core Aspects," *Sustainable Cities and Society* 59.8 (2020): 102143.

comprehensive 10Rs framework, reflecting an expanding commitment to sustainable development that integrates economic, environmental, and social aspects. This evolution represents not only a conceptual maturation but also the diversification of practices and the integration of technological advances, steering the urban CE towards an increasingly sustainable future.

Although there is still no uniform definition of the urban CE, there is a general understanding of the urban CE: (i) it is a closed-loop system of industrial processes and consumer practices which reduces the waste emission; (ii) it seeks to separate economic development from environmental deterioration; (iii) it aims to maximise economic development, reduce environmental pollution and improve human well-being; and (iv) it implements the principles of CE at city level. For more detailed insights, refer to Table 4.

Table 4. Urban CE overview and references

General understanding of the urban CE	Reference
Closed-loop system	Guo et al.(2024) ³⁴ ; Ma et al.(2023) ³⁵ ;Yadav et al.(2023) ³⁶ ;Moraes et al.(2023) ³⁷ ;Maddalene et al.

³⁴ Guo, D., Zhang, S., Hou, H., Zhang, Y., & Xu, H., “Synergistic Evaluation Methodology for Pollution and Carbon Reduction in the Field of Solid Waste Resource Utilization,” *Environmental Impact Assessment Review* 108.5 (2024): 107604.

³⁵ Ma, W., Hao, J. L., Zhang, C., Di Sarno, L., & Mannis, A., “Evaluating Carbon Emissions of China’s Waste Management Strategies for Building Refurbishment Projects: Contributing to a Circular Economy,” *Environmental Science and Pollution Research* 30.4 (2023): 8657-8671.

³⁶ Yadav, H., Soni, U., & Kumar, G., “Analysing Challenges to Smart Waste Management for a Sustainable Circular Economy in Developing Countries: A Fuzzy DEMATEL Study,” *Smart and Sustainable Built Environment* 12.2 (2023): 361-384.

³⁷ Moraes, F. T. F., Gonçalves, A. T. T., Lima, J. P., & da Silva Lima, R., “Transitioning towards a Sustainable Circular City: How to Evaluate and Improve Urban Solid Waste Management in Brazil,” *Waste Management & Research* 41.5 (2023): 1046-1059.

	(2023) ³⁸ ; Wu et al.(2022) ³⁹ ; Shang et al. (2022) ⁴⁰ ;
Economic development and environmental improvement	Moraes et al.(2023) ⁴¹ ; Peiris et al.(2023) ⁴² ; Meng et al.(2021) ⁴³ ; Wang et al.(2021) ⁴⁴
(iii) Maximizing economic and human well-being	Meng et al.(2021) ⁴⁵ ; Li et al. (2021) ⁴⁶ ; Huang et al.(2015) ⁴⁷
(iv) Implementation at the city level	Sinoh et al. (2023) ⁴⁸ ; Shang et al. (2022) ⁴⁹ ;Meng et al.(2021) ⁵⁰ ; Fang et al.(2017) ⁵¹ ; Kosanović et

- ³⁸ Maddalene, T., Youngblood, K., Abas, A., Browder, K., Cecchini, E., Finder, S., Gaidhani, S., Handayani, W., Hoang, X., N., Jaiswal, K., Martin, E., Menon, S., O'Brien, Q., Roy, P., Septiarani, B., Trung, H., N., Voltmer, C., Werner, M., Wong, R., & Jambeck, J. R., "Circularity in Cities: A Comparative Tool to Inform Prevention of Plastic Pollution," *Resources, Conservation and Recycling* 198.11 (2023): 107156.
- ³⁹ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L. "Assessing City's Performance-resource Improvement in China: A Sustainable Circular Economy Framework Approach," *Environmental Impact Assessment Review* 96.5 (2022): 106833.
- ⁴⁰ Shang, Y., Song, M., & Zhao, X., "The Development of China's Circular Economy: From the Perspective of Environmental Regulation," *Waste Management* 149.13 (2022): 186-198.
- ⁴¹ Moraes, F. T. F., Gonçalves, A. T. T., Lima, J. P., & da Silva Lima, R., "Transitioning towards a Sustainable Circular City: How to Evaluate and Improve Urban Solid Waste Management in Brazil," *Waste Management & Research* 41.5 (2023): 1046-1059.
- ⁴² Peiris, M. T. O. V., & Dayarathne, G. L. N., "Application of Life Cycle Framework for Municipal Solid Waste Management: A Circular Economy Perspective from Developing Countries," *Circular Economy and Sustainability* 3.2 (2023): 899-918.
- ⁴³ Meng, M., Wen, Z., Luo, W., & Wang, S., "Approaches and Policies to Promote Zero-waste City Construction: China's Practices and Lessons," *Sustainability* 13.24 (2021): 13537.
- ⁴⁴ Wang, S., Lei, L., & Xing, L., "Urban Circular Economy Performance Evaluation: A Novel Fully Fuzzy Data Envelopment Analysis with Large Datasets," *Journal of Cleaner Production* 324.47 (2021): 129214.
- ⁴⁵ Meng, M., Wen, Z., Luo, W., & Wang, S., "Approaches and Policies to Promote Zero-waste City Construction: China's Practices and Lessons," *Sustainability* 13.24 (2021): 13537.
- ⁴⁶ Li, J., Sun, W., Song, H., Li, R., & Hao, J., "Toward the Construction of a Circular Economy Eco-city: An Emergy-based Sustainability Evaluation of Rizhao City in China," *Sustainable Cities and Society*, 71.8 (2021), 102956.
- ⁴⁷ Huang, Q., Zheng, X., & Hu, Y., "Analysis of Land-use Emergy Indicators Based on Urban Metabolism: A Case Study for Beijing," *Sustainability* 7.6 (2015): 7473-7491.
- ⁴⁸ Sinoh, S. S., Othman, F., & Onn, C. C., "Circular Economy Potential of Sustainable Aggregates for the Malaysian Construction Industry," *Sustainable Cities and Society* 89.2 (2023): 104332.
- ⁴⁹ Shang, Y., Song, M., & Zhao, X., "The development of China's Circular Economy: From the Perspective of Environmental Regulation," *Waste Management* 149.13 (2022): 186-198.
- ⁵⁰ Meng, M., Wen, Z., Luo, W., & Wang, S., "Approaches and Policies to Promote Zero-waste City Construction: China's Practices and Lessons," *Sustainability* 13.24 (2021): 13537.
- ⁵¹ Fang, K., Dong, L., Ren, J., Zhang, Q., Han, L., & Fu, H., "Carbon Footprints of Urban Transition:

	al.(2021) ⁵² ; Ferronato et al.(2021) ⁵³ ; Gao et al.(2021) ⁵⁴ ; Liu et al.(2018) ⁵⁵ ; Wang et al.(2018) ⁵⁶
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3.2.2 Indicators for monitoring and evaluating the urban CE

The theories of CE and sustainable development are both derived from the systems ecology of the 1960s and 1970s. They are described as a vague, value-laden concept. The scholar argues that the CE is essential to attaining the SDGs.⁵⁷ While there is debate on whether the CE is able to necessarily achieve sustainability.⁵⁸ This section presents a description of the urban-level indicators in developing countries up to the present moment. For specific indicators, refer to Appendix Table A2.

Based on the content of Appendix Table A2, Figure 3 illustrates the strength of the association between the principles of CE and the SDGs. From Figure 3, it can be observed that the impact of CE principles on SDGs is multifaceted, but the intensity and specific areas of influence may vary. Notably, CE principles such as Reduce, Recycle, and Recover show a stronger association with environmental SDGs 6, 11, 12, and 13. The principles of Reuse and Repurpose exhibit a significant association with economic-related SDGs 8 and

Tracking Circular Economy Promotions in Guiyang, China,” *Ecological Modelling* 365.23 (2017): 30-44.

⁵² Kosanović, S., Miletić, M., & Marković, L., “Energy Refurbishment of Family Houses in Serbia in Line with the Principles of Circular Economy,” *Sustainability* 13.10 (2021): 5463.

⁵³ Ferronato, N., Ragazzi, M., Portillo, M. A. G., Lizarazu, E. G. G., Viotti, P., & Torretta, V., “How to Improve Recycling Rate in Developing Big Cities: An Integrated Approach for Assessing Municipal Solid Waste Collection and Treatment Scenarios,” *Environmental Development* 29.1 (2019): 94-110.

⁵⁴ Gao, H., Tian, X., Zhang, Y., Shi, L., & Shi, F., “Evaluating Circular Economy Performance Based on Ecological Network Analysis: A Framework and Application at City Level,” *Resources, Conservation and Recycling* 168.5 (2021): 105257.

⁵⁵ Liu, X., Guo, P., Yue, X., Qi, X., Guo, S., & Zhou, X., “Measuring Metabolic Efficiency of the Beijing-Tianjin-Hebei Urban Agglomeration: A Slacks-based Measures Method,” *Resources Policy* 70.1 (2021): 101928.

⁵⁶ Wang, N., Lee, J. C. K., Zhang, J., Chen, H., & Li, H., “Evaluation of Urban Circular Economy Development: An Empirical Research of 40 Cities in China,” *Journal of Cleaner Production* 180.11 (2018): 876-887.

⁵⁷ de Oliveira, C. T., & Oliveira, G. G. A., “What Circular Economy Indicators Really Measure? An Overview of Circular Economy Principles and Sustainable Development Goals,” *Resources, Conservation and Recycling* 190.3 (2023): 106850.

⁵⁸ Millar, N., McLaughlin, E., & Börger, T., “The circular economy: swings and roundabouts?,” *Ecological economics* 158.4 (2019): 11-19.

9. The principles of Repair and Refurbish demonstrate a certain level of association with socially related SDGs 2 and 3.

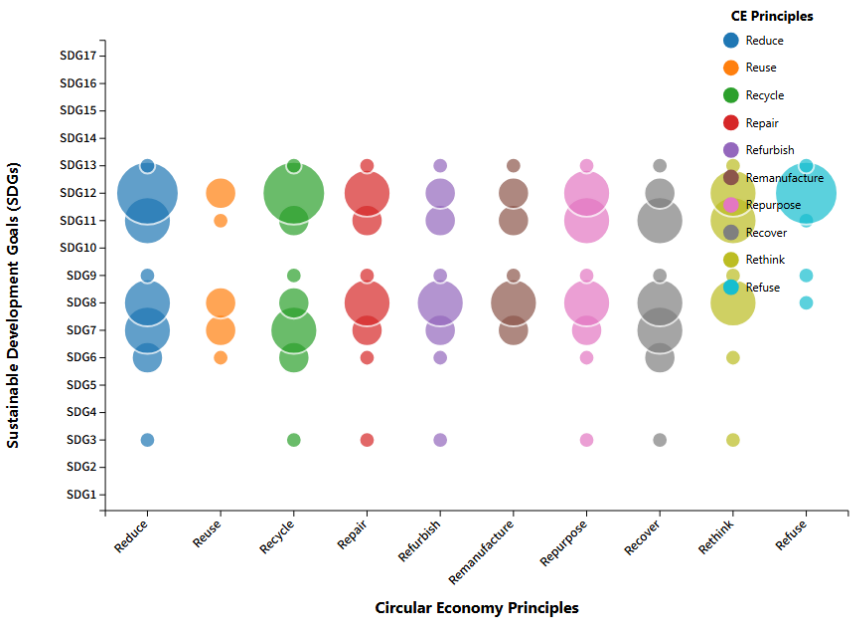


Figure 3. CE principles vs SDGs Bubble Chart

As can be seen from Figure 4, environmental indicators are the most numerous, totaling 9. This is followed by economic indicators, which amount to 5. Social indicators are less represented, with 4 in total. In addition, there are several indicators that encompass intersecting attributes. Specifically, there are 4 indicators that intersect between economic and environmental dimensions, and 3 indicators that intersect between social and environmental dimensions.

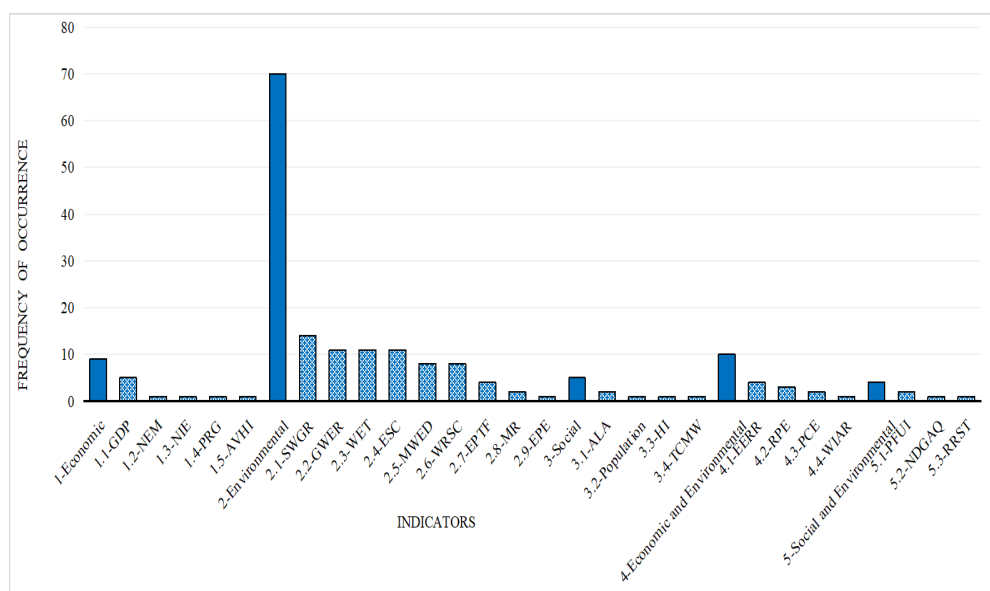


Figure 4. Distribution of Urban CE Indicators

- (i) In environmental science, the Solid Waste Generation and Reuse (SWGR) indicator is the most frequently cited in literature.⁵⁹ Additionally, this indicator is directly linked to SDGs 11 and 12, promoting sustainability in waste management and reducing environmental pollution through improved resource efficiency. Next in prevalence is the indicator of Gas Waste Emissions and Removal (GWER).⁶⁰ It is intimately connected to SDGs 9 and 12, emphasising the significance of diminishing carbon emissions from industrial processes. The indicators of Wastewater Emission and Treatment (WET),⁶¹ and Water Resource Supply and Consumption (WRSC) are critical

⁵⁹ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., "Assessing City's Performance-Resource Improvement in China: A Sustainable Circular Economy Framework Approach," *Environmental Impact Assessment Review* 96.5 (2022): 106833.

⁶⁰ Wang, S., Lei, L., & Xing, L., "Urban Circular Economy Performance Evaluation: A Novel Fully Fuzzy Data Envelopment Analysis with Large Datasets," *Journal of Cleaner Production* 324.47 (2021): 129214.

⁶¹ Dong, L., Fujita, T., Dai, M., Geng, Y., Ren, J., Fujii, M., Wang, Y., & Ohnishi, S., "Towards Preventative Eco-industrial Development: An Industrial and Urban Symbiosis Case in One Typical Industrial City in China," *Journal of Cleaner Production* 114.5 (2016): 387-400.

for the preservation of water resources and the assurance of clean drinking water, which is aligned closely with SDG 6.⁶² Energy Supply and Consumption (ESC) is closely related to SDG 7,⁶³ highlighting the need to improve energy consumption and adopt clean energy. The indicators of Municipal Waste Emission and Disposal (MWED) and Environmental Pollution Treatment Facilities (EPTF) are relevant to both SDGs 6 and 11,⁶⁴ contributing to the process of environmental protection, sustainable resource management, and sustainable urban growth. The Green Coverage Rate (GCR)⁶⁵ is intricately linked to SDGs 15 and 11. It can promote the improvement of the urban ecological environment. Material Recycling (MR),⁶⁶ is connected to SDGs 6 and 7, enhancing the recycling rate of materials usage and waste creation. The indicator of Environmental Protection Expenditure (EPE) is linked to SDG 13.⁶⁷ Through effective environmental protection spending, it can contribute to the achievement of climate action goals.

- (ii) Shifting to economic indicators, Gross Domestic Product (GDP) promotes sustained economic growth and is closely aligned with SDG 8.⁶⁸ The

⁶² Ma, J., Wang, D., Li, X., & Zhang, B., “Inherent Complexity and Early Warning of Zaozhuang Circular Economy System,” *International Journal of Bifurcation and Chaos* 33.04 (2023a): 2350040.

⁶³ Wang, N., Lee, J. C. K., Zhang, J., Chen, H., & Li, H., “Evaluation of Urban Circular Economy Development: An Empirical Research of 40 Cities in China,” *Journal of Cleaner Production* 180.11 (2018): 876-887.

⁶⁴ Prendeville, S., Cherim, E., & Bocken, N., “Circular Cities: Mapping Six Cities in Transition,” *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

⁶⁵ de Oliveira, C. T., & Oliveira, G. G. A., “What Circular Economy Indicators Really Measure? An Overview of Circular Economy Principles and Sustainable Development Goals,” *Resources, Conservation and Recycling* 190.3 (2023): 106850.

⁶⁶ Li, J., Sun, W., Song, H., Li, R., & Hao, J., “Toward the Construction of a Circular Economy Eco-city: An Emergy-Based Sustainability Evaluation of Rizhao City in China,” *Sustainable Cities and Society* 71.8 (2021): 102956.

⁶⁷ Prendeville, S., Cherim, E., & Bocken, N., “Circular Cities: Mapping Six Cities in Transition,” *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

⁶⁸ Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C. A., & Jung, N., “Towards Circular Cities—Conceptualizing Core Aspects,” *Sustainable Cities and Society* 59.8 (2020): 102143.

indicators of Number of Employees in Manufacturing (NEM),⁶⁹ Number of Industrial Enterprises (NIE),⁷⁰ and Proportion of R&D in GDP (PRG) emphasise the demand to upgrade and retrain the industrial workforce to meet the demands of sustainable production, which is associated with SDGs 8 and 9.⁷¹ Lastly, the indicator of Added Value of High-tech Industry (AVHI) encourages the development of high-tech industries, which is linked to SDG 9.⁷²

- (iii) In terms of social indicators, Arable Land Area (ALA),⁷³ emphasises the use and recycling of agricultural land to ensure agricultural sustainability, and is related to SDG 2. The indicator of Population, Health Investment (HI),⁷⁴ Treatment Capacity of Medical Waste (TCMW),⁷⁵ exerts a significant influence on the demand for resources, environmental conservation, and robust social services. This approach is closely related to SDG 3.
- (iv) In the area of convergence between economic prosperity and environmental sustainability, the Energy Economic Return Ratio (EERR) can help to ensure that economic development does not come at the expense of the environment,

⁶⁹ Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C. A., & Jung, N., "Towards Circular Cities—Conceptualizing Core Aspects," *Sustainable Cities and Society* 59.8 (2020):102143.

⁷⁰ de Oliveira, C. T., & Oliveira, G. G. A., "What Circular Economy Indicators Really Measure? An Overview of Circular Economy Principles and Sustainable Development Goals," *Resources, Conservation and Recycling* 190.3 (2023): 106850.

⁷¹ Millar, N., McLaughlin, E., & Börger, T., "The Circular Economy: Swings and Roundabouts?," *Ecological Economics* 158.4 (2019): 11-19.

⁷² de Oliveira, C. T., & Oliveira, G. G. A., "What Circular Economy Indicators Really Measure? An Overview of Circular Economy Principles and Sustainable Development Goals," *Resources, Conservation and Recycling* 190.3 (2023): 106850.

⁷³ Prendeville, S., Cherim, E., & Bocken, N., "Circular Cities: Mapping Six Cities in Transition," *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

⁷⁴ Petit-Boix, A., & Leipold, S., "Circular Economy in Cities: Reviewing How Environmental Research Aligns with Local Practices," *Journal of Cleaner Production* 195.26 (2018): 1270-1281.

⁷⁵ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., "Assessing City's Performance-Resource Improvement in China: A Sustainable Circular Economy Framework Approach," *Environmental Impact Assessment Review* 96.5 (2022): 106833.

thereby supporting the SDGs 7 and 8.⁷⁶ The indicator of Resource Productivity Efficiency (RPE) is connected to SDG 12.⁷⁷ It encourages a reevaluation of resource usage, promoting a green industrial transformation and sustainable development. The Per Capita Energy (PCE) highlights the importance of clean energy in production and utilization, which is consistent with the SDGs 7 and 12.⁷⁸ The indicator of Water-saving Irrigation Area Ratio (WIAR) is aligned with SDGs 6 and 12.⁷⁹ Improving agricultural water management supports sustainable agricultural production practices.

- (v) In the intersection of society and the environment, Pesticide and Fertilizer Use Intensity (PFUI) directly impacts the sustainability of agricultural production, aligning with the SDGs 2 and 12.⁸⁰ The Number of Days with Good Air Quality (NDGAQ) is intricately connected to public health outcomes.⁸¹ The mitigation of air pollution is essential in reducing the incidence of respiratory ailments and a spectrum of health complications. Furthermore, this indicator is consonant with SDGs 3 and 11. The Rate of Rural Sanitary Toilets (RRST) is linked to SDGs 3 and 6.⁸² This indicator not only improves individual hygiene but also has positive externalities on the health of the community as a whole.

⁷⁶ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., “Assessing City’s Performance-Resource improvement in China: A sustainable circular economy framework approach,” *Environmental Impact Assessment Review* 96.5 (2022): 106833.

⁷⁷ Millar, N., McLaughlin, E., & Börger, T., “The circular economy: swings and roundabouts?,” *Ecological economics* 158.4 (2019): 11-19.

⁷⁸ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., “Assessing city’s performance-resource improvement in China: A sustainable circular economy framework approach,” *Environmental Impact Assessment Review* 96.5 (2022): 106833.

⁷⁹ Millar, N., McLaughlin, E., & Börger, T., “The Circular Economy: Swings and Roundabouts?,” *Ecological Economics* 158.4 (2019): 11-19.

⁸⁰ Millar, N., McLaughlin, E., & Börger, T., “The Circular Economy: Swings and Roundabouts?,” *Ecological Economics* 158.4 (2019): 11-19.

⁸¹ Prendeville, S., Cherim, E., & Bocken, N., “Circular Cities: Mapping Six Cities in Transition,” *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

⁸² Millar, N., McLaughlin, E., & Börger, T., “The Circular Economy: Swings and Roundabouts?,” *Ecological Economics* 158 (2019): 11-19.

3.2.3. Methods for monitoring and evaluating the urban CE

This paper reviews a variety of monitoring and evaluation tools mentioned in the current literature. Figure 5 illustrates the main methods that have been adopted.

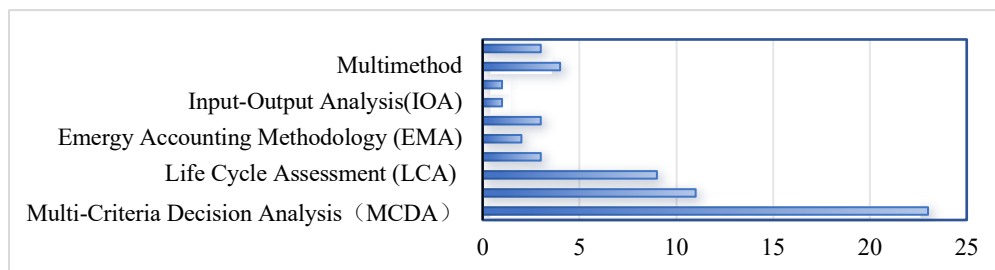


Figure 5. Monitoring and Evaluation Methods Used

- (i) Multi-criteria Decision Analysis (MCDA). In the aforementioned literature, MCDA has been used extensively in various countries and fields, assessing the optimal solutions by considering multiple criteria and objectives.⁸³ The most frequently used approach is the DEMATEL method,⁸⁴ which analyses the causal relationships between factors and assists decision makers in identifying key barriers and drivers within the system.⁸⁵ The entropy method is also employed as a secondary technique.⁸⁶ However, the effectiveness of MCDA may be affected by

⁸³ Ferronato, N., Moresco, L., Guisbert Lizarazu, G. E., Gorrity Portillo, M. A., Conti, F., & Torretta, V., "Comparison of Environmental Impacts Related to Municipal Solid Waste and Construction and Demolition Waste Management and Recycling in a Latin American Developing City," *Environmental Science and Pollution Research* 30 (2021): 8548-8562.

⁸⁴ Feng, J., Xu, S. X., Xu, G., & Cheng, H., "An Integrated Decision-Making Method for Locating Parking Centers of Recyclable Waste Transportation Vehicles," *Transportation Research Part E: Logistics and Transportation Review* 157.1 (2022): 102569.

⁸⁵ Bui, T. D., Tsai, F. M., Tseng, M. L., Wu, K. J., & Chiu, A. S., "Effective Municipal Solid Waste Management Capability Under Uncertainty in Vietnam: Utilizing Economic Efficiency and Technology to Foster Social Mobilization and Environmental Integrity," *Journal of Cleaner Production* 259.18 (2020): 120981.

⁸⁶ Liu, Q., Yao, X., & Pei, L., "Empirical Evidence of Coupling and Coordination between Circular Economy and Foreign Trade Based on Big Data," *Applied Mathematics and Nonlinear Sciences* 9.1 (2024).

the criteria selected, weight allocation, and data quality.⁸⁷

- (ii) Digital technology. In the documents gathered, the majority of scholars have harnessed digital technologies to boost the efficacy, precision, and eco-friendliness of waste management systems. Geographic Information Systems (GIS),⁸⁸ a contemporary technique for geographical data analysis,⁸⁹ has been deployed to scrutinise data across various studies,⁹⁰ and has also been used to oversee and appraise the efficacy.⁹¹ Moreover, many academics have used digital technologies to refine the precision and dependability of waste estimation methodologies.⁹² Big data analytics have been utilised to assess environmental impacts and monitor waste management efficiency indicators.⁹³ Nonetheless, it is apparent that the utilisation of digital technologies at the urban level is still somewhat confined,⁹⁴ and there is a need for a broader application and

⁸⁷ Jacintos Nieves, A., & Delgado Ramos, G. C., “Advancing the Application of a Multidimensional Sustainable Urban Waste Management Model in a Circular Economy in Mexico City,” *Sustainability* 15.17 (2023): 12678.

⁸⁸ Cheng, K. L., Hsu, S. C., Li, W. M., & Ma, H. W., “Quantifying Potential Anthropogenic Resources of Buildings through Hot Spot Analysis,” *Resources, Conservation and Recycling* 133.6 (2018): 10-20.

⁸⁹ Sharma, N., Kalbar, P. P., & Salman, M., “Development of Building Stock Model for An Emerging City in India: Learnings for Enabling Circular Economy in the Built Environment,” *Journal of Industrial Ecology* 28.2 (2024): 13483.

⁹⁰ Long, Y., Song, Q., Huang, B., Zeng, X., & Wu, H., “Characterizing Temporal and Spatial Characteristics of Urban Building Material Metabolism and Embodied Carbon Emissions through a 4D GIS-MFA-LCA Model,” *Resources, Conservation and Recycling* 206.7 (2024): 107642.

⁹¹ Ferronato, N., Preziosi, G., Portillo, M. A. G., Lizarazu, E. G. G., & Torretta, V., “Assessment of Municipal Solid Waste Selective Collection Scenarios with Geographic Information Systems in Bolivia,” *Waste Management* 102.2 (2020): 919-931.

⁹² Maged, A., Elshaboury, N., & Akanbi, L., “Data-driven Prediction of Construction and Demolition Waste Generation Using Limited Datasets in Developing Countries: An Optimized Extreme Gradient Boosting Approach,” *Environment, Development and Sustainability* 26.4 (2024): 1-25.

⁹³ Galván, S. L., & Bielsa, R. O., “Use of Life Cycle Assessment for Estimating Impacts of Waste-to-energy Technologies in Solid Waste Management Systems: The Case of Buenos Aires, Argentina,” *Environmental Science and Pollution Research* 31.7 (2024): 9992-10012.

⁹⁴ Safaeian, M. R., Ardestani, M., & Sarang, A., “The Perspective of a Smart City by Endorsing the Nexus Bermuda Triangle with the Risk Assessment of Polluted Water Reuse in Integrated Water and Food Security Management: The Case of Semnan, Iran,” *Water Reuse* 12.4 (2022): 403-419.

evaluation within the research domain.⁹⁵

- (iii) Life Cycle Assessment (LCA). In the reviewed literature, the LCA method has been extensively applied across various developing countries, covering various fields. LCA can serve as an evaluative instrument capable of being integrated with other methodologies, offering a more comprehensive analysis and a suite of solutions. Many studies exemplified this approach, highlighting the versatility and effectiveness of LCA.⁹⁶ However, LCA requires specialist knowledge and significant time and resources to implement.⁹⁷
- (iv) Material Flow Analysis (MFA). In the collected literature, the MFA method is commonly applied to measure material circulation at the urban level,⁹⁸ thereby assessing resource efficiency and environmental impacts.⁹⁹ However, the MFA method has a high data demand and requires high levels of data accuracy and completeness.¹⁰⁰
- (v) Emergy Accounting Methodology (EMA). The EMA method has been utilised for evaluating the value of energy.¹⁰¹ But the application of EMA

⁹⁵ Elshaboury, N., & AlMetwaly, W. M., "Modeling Construction and Demolition Waste Quantities in Tanta City, Egypt: A Synergistic Approach of Remote Sensing, Geographic Information System, and Hybrid Fuzzy Neural Networks," *Environmental Science and Pollution Research* 30.48 (2023): 106533-106548.

⁹⁶ Moraes, F. T. F., Gonçalves, A. T. T., Lima, J. P., & da Silva Lima, R., "Transitioning towards a Sustainable Circular City: How to Evaluate and Improve Urban Solid Waste Management in Brazil," *Waste Management & Research* 41.5 (2023):1046-1059.

⁹⁷ Wang, H., Zhang, N., Duan, H., & Dong, L., "Pathways to Sound Management of Excavated Soil and Rock: A Case Study in Shenzhen," *Journal of Cleaner Production* 458.25 (2024): 142383.

⁹⁸ Huang, Q., Zheng, X., & Hu, Y., "Analysis of Land-Use Emergy Indicators Based on Urban Metabolism: A Case Study for Beijing," *Sustainability* 7.6 (2015): 7473-7491.

⁹⁹ Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., Fujii, M., Zhang, W., Zhang, N., & Liu, Z., "Eco-benefits Assessment on Urban Industrial Symbiosis Based on Material Flows Analysis and Energy Evaluation Approach: A Case of Liuzhou City, China," *Resources, Conservation and Recycling* 119.4 (2017): 78-88.

¹⁰⁰ Gao, H., Tian, X., Zhang, Y., Shi, L., & Shi, F., "Evaluating Circular Economy Performance Based on Ecological Network Analysis: A Framework and Application at City Level," *Resources, Conservation and Recycling* 168.5 (2021): 105257.

¹⁰¹ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., "Assessing City's Performance-Resource Improvement in China: A Sustainable Circular Economy Framework Approach," *Environmental Impact*

may lack standardised procedures, which makes it complicated to compare the various studies.

- (vi) Data Envelopment Analysis (DEA). Wang et al. used DEA to assess the efficiency of the urban CE, especially when dealing with large datasets and the presence of uncertainty.¹⁰² In practice, DEA can be used in combination with supplementary approaches to provide a more comprehensive evaluation.
- (vii) Ecological Network Analysis (ENA). ENA can build urban material metabolic networks to identify key nodes and ecological relationships.¹⁰³ However, this approach may require expertise in ecology and network analysis.
- (viii) Some scholars have used an integration of various approaches to comprehensively measure system performance.¹⁰⁴ These combinations of multi-methods contribute to a comprehensive evaluation of system performance and sustainability.¹⁰⁵ A few studies have also used other non-mainstream methods.

Table 5 examines the application of assessment tools in evaluating urban CE against the environmental, economic, and social dimensions of SDGs. The MCDA method is notably comprehensive, addressing all three dimensions. Most tools, such as LCA, MFA, and Input-Output Analysis (IOA), predominantly focus on environmental aspects. DEA is more concerned with economic efficiency and resource use of CE. Although fewer tools

Assessment Review 96.5 (2022): 106833.

¹⁰² Petit-Boix, A., & Leipold, S., "Circular Economy in Cities: Reviewing How Environmental Research Aligns with Local Practices," *Journal of Cleaner Production* 195.26 (2018): 1270-1281.

¹⁰³ Millar, N., McLaughlin, E., & Börger, T., "The Circular Economy: Swings and Roundabouts?," *Ecological Economics* 158.4 (2019): 11-19.

¹⁰⁴ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., "Assessing city's performance-resource improvement in China: A sustainable circular economy framework approach," *Environmental Impact Assessment Review* 96.5 (2022): 106833.

¹⁰⁵ Liu, W., Zhan, J., Li, Z., Jia, S., Zhang, F., & Li, Y., "Eco-efficiency evaluation of regional circular economy: A case study in Zengcheng, Guangzhou," *Sustainability* 10.2 (2018): 453.

directly address social dimensions, a multi-method approach can offer a broader perspective, including social impacts. To fully assess the contributions of urban CE to SDGs, a combination of tools is required, spanning environmental, economic, and social aspects.

Table 5. CE Assessment Tools and Their Dimensions to SDGs

Tool	Methodology source	Eco.	Env.	Soc.
MCDA	Ferronato et al., 2019; ¹⁰⁶ Bui et al., 2020; ¹⁰⁷ Feng et al., 2022; ¹⁰⁸ Shi et al., 2019; ¹⁰⁹ Zhang et al., 2023; ¹¹⁰ Meas et al., 2022; ¹¹¹ Yadav et al., 2023; ¹¹² do Nascimento et al., 2023; ¹¹³ Moraes et al., 2023; ¹¹⁴ Haseli et al., 2023) ¹¹⁵	*	*	*

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- ¹⁰⁶ Ferronato, N., Ragazzi, M., Portillo, M. A. G., Lizarazu, E. G. G., Viotti, P., & Torretta, V., "How to Improve Recycling Rate in Developing Big Cities: An Integrated Approach for Assessing Municipal Solid Waste Collection and Treatment Scenarios," *Environmental Development* 29 (2019): 94-110.
- ¹⁰⁷ Bui, T. D., Tsai, F. M., Tseng, M. L., Wu, K. J., & Chiu, A. S., "Effective Municipal Solid Waste Management Capability under Uncertainty in Vietnam: Utilizing Economic Efficiency and Technology to Foster Social Mobilization and Environmental Integrity," *Journal of Cleaner Production* 259 (2020): 120981.
- ¹⁰⁸ Feng, J., Xu, S. X., Xu, G., & Cheng, H., "An Integrated Decision-Making Method for Locating Parking Centers of Recyclable Waste Transportation Vehicles," *Transportation Research Part E: Logistics and Transportation Review* 157 (2022): 102569.
- ¹⁰⁹ Shi, J., Zhou, J., & Zhu, Q., "Barriers of a Closed-loop Cartridge Remanufacturing Supply Chain for Urban Waste Recovery Governance in China," *Journal of Cleaner Production* 212 (2019): 1544-1553.
- ¹¹⁰ Zhang, A., Xie, S., Gong, Y., Li, C., & Liu, Y., "Barriers to Compulsory Waste Sorting for a Circular Economy in China," *Journal of Environmental Management* 342 (2023): 118180.
- ¹¹¹ Meas, S., Kuok, F., & Promentilla, M. A. B., "Application of DEMATEL for Barriers Analysis of Co-management of Urban Bio-wastes in Phnom Penh, Cambodia," *Chemical Engineering Transactions* 94 (2022): 367-372.
- ¹¹² Yadav, H., Soni, U., & Kumar, G., "Analysing Challenges to Smart Waste Management for a Sustainable Circular Economy in Developing Countries: a Fuzzy DEMATEL Study," *Smart and Sustainable Built Environment* 12.2 (2023): 361-384.
- ¹¹³ do Nascimento Lopes, E. R., & da Silva, M. V., "Projection, Potential and Managerial Alternatives for Solid Waste Management in Municipal Consortia," *Environment, Development and Sustainability* 27.2 (2025): 4571-4590.
- ¹¹⁴ Moraes, F. T. F., Gonçalves, A. T. T., Lima, J. P., & da Silva Lima, R., "Transitioning towards a Sustainable Circular City: How to Evaluate and Improve Urban Solid Waste Management in Brazil," *Waste Management & Research* 41.5 (2023): 1046-1059.
- ¹¹⁵ Haseli, G., Torkayesh, A. E., Hajiaghaei-Keshteli, M., & Venghaus, S., "Sustainable Resilient Recycling Partner Selection for Urban Waste Management: Consolidating Perspectives of Decision-makers and

	(Wu et al., 2022; ¹¹⁶ Ma et al., 2023; ¹¹⁷ Sharma et al.,2021; ¹¹⁸ Wang et al.,2018; ¹¹⁹ Liu et al., 2024) ¹²⁰	*	*	
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In addition to the aforementioned applications, digital technologies have significant implications for the assessment of the economic, environmental, and social dimensions of the SDGs, with a particularly notable role in environmental monitoring and management. A review of the literature and case study analysis reveals that digital technologies hold substantial potential for enhancing the efficiency and effectiveness of urban CE practices. For instance, Ferronato et al. (2020) employed GIS to evaluate selective collection scenarios for municipal solid waste in Bolivia, which led to significant improvements in collection efficiency and material recovery rates.¹²¹ Liu et al. (2024) utilised big data analytics to monitor and predict waste generation patterns, optimise resource allocation, and assess the environmental impacts of waste management practices.¹²² Maged et al. (2024) developed a data-driven predictive model for waste sorting and recycling processes,

Experts,” *Applied Soft Computing* 137 (2023): 110120.

¹¹⁶ Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L., “Assessing City’s Performance-resource Improvement in China: A Sustainable Circular Economy Framework Approach,” *Environmental Impact Assessment Review* 96 (2022): 106833.

¹¹⁷ Ma, J., Wang, D., Li, X., & Zhang, B., “Inherent Complexity and Early Warning of Zaozhuang Circular Economy System,” *International Journal of Bifurcation and Chaos* 33.4 (2023): 2350040.

¹¹⁸ Sharma, N., Kalbar, P. P., & Salman, M., “Development of Building Stock Model for An Emerging City in India: Learnings for Enabling Circular Economy in the Built Environment,” *Journal of Industrial Ecology* 28.4 (2024): 751-767.

¹¹⁹ Wang, N., Lee, J. C. K., Zhang, J., Chen, H., & Li, H., “Evaluation of Urban Circular Economy Development: An Empirical Research of 40 Cities in China,” *Journal of Cleaner Production*, 180 (2018): 876-887.

¹²⁰ Liu, Q., Mao, X., & Pei, L., “Empirical Evidence of Coupling and Coordination between Circular Economy and Foreign Trade Based on Big Data,” *Applied Mathematics and Nonlinear Sciences* 9.1 (2024): 11.

¹²¹ Ferronato, N., Preziosi, G., Portillo, M. A. G., Lizarazu, E. G. G., & Torretta, V., “Assessment of Municipal Solid Waste Selective Collection Scenarios with Geographic Information Systems in Bolivia,” *Waste Management* 102 (2020): 919-931.

¹²² Liu, Q., Mao, X., & Pei, L., “Empirical Evidence of Coupling and Coordination between Circular Economy and Foreign Trade Based on Big Data,” *Applied Mathematics and Nonlinear Sciences* 9.1 (2024): 11.

thereby increasing accuracy and efficiency.¹²³

4. Discussion

4.1 Main finding

The concept of an urban CE represents a comprehensive and integrated approach to achieving efficient resource utilisation, environmental protection, social welfare, and economic prosperity. It is evident that the urban CE is a multifaceted concept, rich in depth and complexity. The majority of the literature on the CE emphasises the core principles of reduce, reuse, recycle, and recovery.¹²⁴ In contrast to the majority of studies, this research, by systematically categorising the extant literature based on urban CE frameworks, reveals that the incorporation of these principles into urban planning represents an emerging domain with significant potential for innovative advancements. The 3Rs principles are universally acknowledged as the cornerstone of CE implementations. These principles emphasise reducing resource consumption, extending the useful product lifespan and materials by reusing and recycling waste to create a sustainable economic framework. However, as the urban CE continues to evolve, the principles have expanded from 3Rs to the comprehensive 10Rs, encompassing a broader range of sustainable practices and considerations.

Secondly, compared with Corona et al.,¹²⁵ our study not only focuses on the indicators of urban CE but also examines how these indicators are linked to the SDGs. A comprehensive evaluation of the relevant indicators is carried out through the lens of the principles of the CE and the SDGs. Environmental indicators occupy a dominant position

¹²³ Maged, A., Elshaboury, N., & Akanbi, L., "Data-driven Prediction of Construction and Demolition Waste Generation Using Limited Datasets in Developing Countries: An Optimized Extreme Gradient Boosting Approach," *Environment, Development and Sustainability* (2024): 1-25.

¹²⁴ Hossain, M., Park, S., Suchek, N., & Pansera, M., "Circular Economy: A Review of Review Articles," *Business Strategy and the Environment* 33.7 (2024): 7077-7099.

¹²⁵ Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E., "Towards Sustainable Development through the Circular Economy-A Review and Critical Assessment on Current Circularity Metrics," *Resources, Conservation and Recycling* 151 (2019): 104498.

among urban development indicators, significantly outnumbering those of the economic and social aspects. The most commonly used environmental indicators are waste emission and treatment indicators such as SWGR, GWER, WET, MWED, and EPTF. This is followed by indicators of energy resource supply and consumption, such as WRSC and ESC. Environmental indicators are closely intertwined with various SDGs, particularly SDGs 6, 7, 9, 11, 12, 13, and 15, collectively fostering resource conservation, environmental protection, and ecological sustainability. Economic indicators, exemplified by GDP, reflect the integration of economic growth with sustainable practices. This approach aligns with both SDGs 8 and 9. Social indicators, such as ALA, Population, HI, and TCMW, are correlated with SDGs 2 and 3. At the confluence of economic and environmental spheres, indicators exemplified by EERR, RPE, PCE, and WIAR are linked to SDGs 6, 7, 8, and 12, thereby enhancing resource efficiency and advocating for environmental sustainability. In the sphere of social and environmental indicators, including PFUI, NDGAQ, and RREST, support SDGs 2, 3, 6, 11, and 12. This integrated approach underscores a holistic dedication to sustainability, including both social and environmental areas. Our analysis revealed that the CE principles most pertinent to the SDGs among the indicators under consideration are, in descending order of relevance, ‘Reduce’, ‘Recycle’, ‘Repurpose’, ‘Repair’, ‘Refurbish’, ‘Reuse’, ‘Rethink’, ‘Recover’, ‘Remanufacture’, and ‘Refuse’.

Finally, there is a great diversity of approaches to monitoring and assessing the urban CE. However, each method is not foolproof and has its own advantages and limitations. In alignment with the researches of Sassanelli et al.¹²⁶ and De Pascale et al.,¹²⁷ the present study undertakes a comprehensive comparative analysis of the prevalent methodologies within the domain. From collected literature, relatively large amounts of studies use MCDA and LCA methods. These methods are flexible and can be applied to evaluation studies in

¹²⁶ Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A., “A Taxonomy of Circular Economy Indicators,” *Journal of Cleaner Production* 207 (2019): 542-559.

¹²⁷ De Pascale, A., Di Vita, G., Giannetto, C., Ioppolo, G., Lanfranchi, M., Limosani, M., & Szopik-Depczyńska, K., “The Circular Economy Implementation at the European Union Level. Past, Present and Future,” *Journal of Cleaner Production* 423 (2023): 138658.

most industries, but LCA requires a high level of data quality, and MCDA is affected by the weighting of criteria. Similarly, several other methods have their own strengths and weaknesses. MFA can quantify material flows in cities but necessitates a considerable extent of data accuracy and completeness. The EMA's method again lacks comparability. DEA provides better comparability, but it is still not comprehensive enough and needs further improvement. In addition to all kinds of traditional evaluation tools, some scholars have recently started to use data science techniques for evaluation.¹²⁸ Many scholars believed that these emerging technologies can effectively enhance the effectiveness and accuracy of waste management, but the existing study is only in individual industries and fields, with relatively scant application at the urban level. The findings of our study appear to suggest that considering some integrated approaches may lead to an effective means of overcoming the limitations inherent to each approach.

4.2 Limitations of current research and future research agenda

Despite the significant potential of the urban CE for the SDGs, this study identifies several remaining gaps and shortcomings. First, current indicators concentrate primarily on economic and ecological factors and may not adequately reflect the importance of social dimensions, such as quality education (SDG 4), gender equality (SDG 5), and reducing inequalities (SDG 10). Second, while the existence of various monitoring and evaluation methodologies, the lack of standardised protocols can pose challenges in comparing and consolidating findings across studies. Third, digital technologies offer innovative ways to assess the urban CE, but their general adoption and proven efficiency in real-life implementation are areas that deserve further validation and exploration. Fourth, data may lack accuracy and representativeness due to limited access, thereby affecting the evaluation outcomes. Fifth, current research may mainly focus on short-term effects, neglecting a comprehensive evaluation of long-term effects. This suggests the requirement for a more

¹²⁸ Fatimah, Y. A., Govindan, K., Sasongko, N. A., & Hasibuan, Z. A., "The Critical Success Factors for Sustainable Resource Management in Circular Economy: Assessment of Urban Mining Maturity Level," *Journal of Cleaner Production* 469.36 (2024): 143084.

balanced method that takes into account not only the prompt results but also the lasting impacts of urban CE strategies.

Future research will continue to explore new theoretical and practical avenues while filling the gaps in the current research. Some trends and potential gaps for subsequent studies are outlined below: First, future research will focus on social indicators such as SDG 4 (Quality Education), SDG 5 (Gender Equality), and SDG 10 (Reduced Inequalities), exploring their specific connections with the CE and developing relevant assessment tools and methodologies. Second, to develop a set of broadly standardised evaluation frameworks to make it easier to compare the progress of different cities or projects in their CE practices. Third, future research will integrate digital technologies to optimise the monitoring and evaluation of the urban CE. Fourth, to develop and validate new methods specifically for evaluating uncertainty in the urban CE. Fifth, subsequent studies will establish mechanisms to track the long-term social, economic, and environmental impacts of CE practices. Table 6 delineates the existing research gaps and prospective avenues for future investigation.

Table 6. Major gaps and Future research

Thematic	Major gaps	Future research	Refer
Indicators	Relative absence of social indicators.	Increased attention to the impact of the CE on social dimensions, such as SDG4, 5, 10.	Mies et al., 2021 ¹²⁹
Evaluation	Data may lack accuracy.	Developing innovative approaches for evaluating uncertainty.	Reike et al., (2018) ¹³⁰
	Lack of standards assess to compare evaluation results.	Developing a widely set of standards evaluation frame.	Papageorgiou et al.,

¹²⁹ Mies, A., & Gold, S., "Mapping the Social Dimension of the Circular Economy," *Journal of Cleaner Production* 321.44 (2021): 128960.

¹³⁰ Reike, D., Vermeulen, W. J., & Witjes, S., "The Circular Economy: New or Refurbished as CE 3.0?—Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options," *Resources, Conservation and Recycling* 135.8 (2018): 246-264.

			(2021) ¹³¹
	Role of technology not fully considered.	Integrate more of these technologies to optimise the monitoring and evaluation.	Wang et al. (2020) ¹³²
	Lack of long-term monitoring and evaluation.	Conduct long-term tracking on CE practices in specific cities or regions.	Prendeville et al. (2018) ¹³³

5. Conclusions

This review identifies the significant prospect of the urban CE to promote sustainability in developing countries. As a model, the urban CE is closely linked to the SDGs through optimising resource efficiency and reducing waste generation. This article conducts an integrative review, using keyword identification to describe the relationships between CE principles and the SDGs for monitoring and evaluating urban CE in developing countries. The key findings can be summarised as:

(i) The essence of urban CE revolves around the fundamental 3Rs principles, which are essential for conserving resources and the preservation of the ecosystem. As the 3Rs evolve to the 10Rs, the urban CE will integrate a richer set of connotations.

(ii) The comprehensive evaluation of urban development indicators highlights the primacy of environmental considerations in sustainable urban planning. Environmental indicators predominantly correlate with the SDGs 6, 7, 9, 11, 12, 13, and 15. Economic indicators, such as GDP, correlate with SDGs 8 and 9. Social indicators relate to SDGs 2

¹³¹ Papageorgiou, A., Henrysson, M., Nuur, C., Sinha, R., Sundberg, C., & Vanhuysse, F., "Mapping and Assessing Indicator-based Frameworks for Monitoring Circular Economy Development at the City-level," *Sustainable Cities and Society* 75.12 (2021): 103378.

¹³² Wang, H., Schandl, H., Wang, X., Ma, F., Yue, Q., Wang, G., Wang, Y., Wei, Y., Zhang, Z., & Zheng, R., "Measuring Progress of China's Circular Economy," *Resources, Conservation and Recycling*, 163.12 (2020): 105070.

¹³³ Prendeville, S., Cherim, E., & Bocken, N., "Circular Cities: Mapping Six Cities in Transition," *Environmental Innovation and Societal Transitions* 26.1 (2018): 171-194.

and 3. At the intersection of the economic and environmental spheres, indicators such as resource productivity promote the fulfillment of SDGs 6, 7, 8, and 12. In addition, social and environmental indicators support SDGs 2, 3, 6, 11, and 12.

(iii) Even though a variety of monitoring and evaluation methods are used, the implementation process still faces challenges in accuracy of data, standardisation, and the requirement for specialised skills. Emerging digital technologies offer new chances to enhance the reliability and efficiency of evaluations. However, their integration into the urban CE is still at an exploratory stage.

In accordance with the above results, the subsequent targeted suggestions are presented for policymakers:

First, governments are building cross-sectoral alliances by forming interdisciplinary task forces to align CE policies with SDG targets and other relevant policy initiatives to ensure harmonisation and maximise synergies. Concurrently, it is imperative for governments to integrate the 10R principles into their urban planning policies to ensure a comprehensive approach to resource efficiency and waste reduction. Second, governments should invest in a robust data infrastructure and establish standards for data collection and reporting. On one hand, the deployment of digital technologies, including GIS, big data analytics, and the IoT, can significantly enhance the precision and accessibility of data. On the other hand, the establishment of data-sharing platforms can foster collaboration and facilitate the exchange of knowledge among cities and regions. Third, urban planners should collaborate with international experts to develop a comprehensive set of CE indicators aligned with the SDGs and establish a certification system for urban circularity. Fourth, policymakers should seek a strategic balance that integrates long-term sustainability planning with the benefits of short-term action, ensuring that immediate action delivers actual environmental and societal benefits while laying the foundations for a robust long-term CE strategy.

While our study has uncovered several significant trends and insights in this field, it is not without limitations that warrant attention in subsequent research. One such limitation is the disproportionate number of papers from China within our sample. This

overrepresentation stems from China's substantial publication volume in this area, highlighting the country's active involvement in research. Fully cognizant of the necessity for sample balance to ensure the reliability and generalizability of research findings, we plan to address this issue by expanding our data sources to include a wider spectrum of countries and regions in our future research endeavours.

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- and the Environment* 31.4 (2022b): 1249-1274.
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Appendix

Table A1. Urban CE Definition and Corresponding CE Principles

No	Authors	Publication Year	Urban CE Definition	Corresponding CE Principles
1	Guo et al.	2024	The theory of a “Zero-Waste City” emphasizes recovery from waste, which is able to significantly alleviate environmental problems associated with waste disposal. At the same time, it reduces the ecological damage and carbon emissions associated with the mining of materials.	Refuse ; Reduce ; Recycle ; Reuse ; Repurpose ; Repair ; Refurbish ; Rethink; Recover
2	Ma et al.	2023	This concept is based on analyzing the relationship between economic and natural systems (Su et al., 2013). China's circular economy concept mirrors those inherent in Japan and Germany, based on the principles of reduce, reuse, and recycle (Troschinetz and Mihelcic, 2009; Xu, 2007).	Reduce; Reuse; Recycle;
3	Yadav et al.	2023	Resources are amenable to recycling, reuse, and repurposing, thereby optimizing the extraction of inherent value.	Reduce, Reuse, Recycle, Repurpose
4	Ma et al.	2023	An economic system designed to eliminate residual materials by maintaining products in circulation through the recycling	Reduce ; Reuse ; Recycle ; Recover ; Rethink ; Repair ;

			of materials, thereby reducing the demand for new resources and environmental destruction.	Refurbish ; Remanufacture ; Repurpose
5	Sinoh et al.	2023	CE transforms waste from one industry into valuable products for another industry. It adopts the “reuse-recycle-remanufacture” principles tackle environmental challenges while offering social and economic advantages.	Reuse; Recycle; Remanufacture
6	Moraes et al.	2023	CE encourages economic strategies that separate economic activity from resource consumption. It aims to preserve the functionality of products while keeping elements, resources, and nutrients in use for an extended period. As a result, urban areas are able to close material loops, reducing the utilization of hazardous resources and the production of waste.	Reduce; Reuse; Recycle; Recover; Remanufacture
7	Peiris et al.	2023	CE is a notion intended to restore and regenerate material loops while reducing waste. Establishing a hierarchy of waste management and assessing the advantages and disadvantages throughout the procedure is essential for achieving this goal.	Reduce; Reuse; Recycle; Recover; Rethink; Repair; Refurbish; Remanufacture

			The cyclical perspective departs from the traditional economic model (make-use-waste) to a cyclical behavior change (make-use-renew), focusing on the equilibrium between economic growth and environmental protection in the best possible way.	
8	Maddalene et al.	2023	A systematic approach that not only focuses on material recycling or waste management, but also optimizes the system to minimize material consumption, sustain resource availability, and prevent waste production.	Reduce; Reuse; Recycle; Recover Rethink; Repair; Refurbish; Remanufacture
9	Wu et al.	2022	CE is a sustainable paradigm focused on reducing discarded materials through design, perpetuating the utility of products, materials, and resources within economic activities via strategies of reuse, recycling, and regeneration.	Reduce, Reuse , Recycle , Recover, Rethink, Refurbish, Remanufacture, Repurpose
10	Zhao et al.	2022	CE is an ecosystem economic model that leverages ecological principles to direct the economic endeavors of human societies. In the natural ecosystem, ecological equilibrium is realized through the interplay of energy	Rethink, Reduce, Reuse, Recycle, Recover;

			conversion and material recycling, ensuring a state of enduring stability and sustainability	
11	Shang et al.	2022	CE signifies a social and economic production system predicated on the recovery and recycling of resources. It is distinguished by its commitment to minimal environmental pollution, optimized resource conservation, and enhanced operational efficiency, strictly following the core tenets of reduction, reuse, and recycling.	Reduce, Reuse, Recycle
12	Liu et al.	2021	Urban metabolic efficiency, calculated as the proportion of resource flows, is a pivotal indicator of resource and energy optimization within cities. Elevated levels of this efficiency indicator not only denote a superior integration and utilization of resources but also correlate with diminished environmental ramifications of urban progression.	Reduce, Recover, Reuse, Recycle, Rethink, Refurbish, Repair, Repurpose, Remanufacture

13	Meng et al.	2021	Adhering to the natural principle of waste minimization, closed-loop material flow systems are integral	Reduce, Reuse, Recycle, Recover, Refurbish,
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			to zero-waste initiatives, which in turn, propel the advancement of circular economy practices. The embrace of these paradigms has led to the implementation of production models that prioritize resource efficiency and curtail the deposition of solid waste in landfills. This strategic shift is instrumental in forging an equilibrium that harmonizes economic viability, environmental sustainability, and societal well-being	Remanufacture, Repurpose, Rethink
14	Fang et al.	2017	Innovative across systems, the circular economy enhances resource efficiency and designs out waste, critical for urban transformation by extending the "3Rs" to include urban symbiosis and sustainable supply chains	Rethink, Reduce, Reuse, Recycle, Repurpose, Recover, Repair, and Refurbish.
15	Kosanović et al.	2021	Within the realm of construction, CE is essentially achieved by reducing the use of building materials and maximizing the utilization of their closed-loop, thereby enhancing the efficiency of building materials.	Reduce, Reuse, Recycle, Recover, Repurpose

16	Ferronato et al.	2021	By preventing, reducing, recycling, and reusing, waste generation can be significantly reduced.	Refuse ; Reduce ; Recycle ; Reuse
17	Sharma	2021	Urban mining is a concept that has	Reduce, Reuse,

	et al.		evolved from the idea of landfill mining; it aims to recycle urban waste and utilize it as much as possible throughout the supply process.	Recycle, Recover, Rethink
18	Lu et al.	2021	Construction waste denotes solid waste from construction operations, renewal work, or demolition efforts.	Reduce; Reuse; Recycle; Recover;
19	Wang et al.	2021	CE framework is an innovative economic framework designed to effectively address issues related to resource use and the environment, separating economic prosperity from environmental degradation.	Reduce; Reuse; Recycle; Recover; Rethink; Repair; Refurbish; Remanufacture; Repurpose
20	Gao et al.	2021	CE, grounded in the 3Rs principles, is considered an economic paradigm that promotes resource conservation and recycling to achieve sustainable development.	Reduce; Reuse; Recycle

21	Li et al.	2021	CE can be adopted as a sustainable urban growth strategy that minimizes the impact of economic processes on the ecosystem by the circulation of four key elements: enterprises, industries, regions, and society, as well as the material cycles within the city's subsystems and their internal boundaries.	Reduce; Reuse; Recycle; Remanufacture; Rethink
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22	Rathore et al.	2020	Within the CE framework, the application of recycling and reuse systems facilitates the sustainable circulation of resources, bolstering economic vitality. Concurrently, it curtails environmental degradation and lessens the financial burden on production processes, all the while augmenting the reuse of waste, in accordance with publication's standards for precision and impact.	Reduce; Reuse; Recycle; Recover; Refurbish; Repair; Remanufacture; Repurpose
23	Liu et al.	2018	CE adheres to the guidelines of reduce, reuse, and recycle (the 3Rs), aiming to reduce pollutant generation, promote sustainable manufacturing, and reduce the input of resource consumption in the production activities.	Reduce; Reuse; Recycle
24	Wang et al.	2018	CE represents a sustainable framework that minimizes resource consumption, pollutant emission, and energy leakage by reducing, circling, and minimizing the loops of resources.	Reduce; Rethink; Rethink; Reuse; Recycle

25	de Andrade et al.	2017	The circular economy is designed to revolutionize conventional linear economic models that follow a manufacturing-usage-disposal sequence. It seeks to elevate the efficiency of resource utilization, thereby diminishing material demand and the generation of waste, aligning with the principles of sustainable and regenerative economic practices.	Rethink, Reduce, Reuse, Recycle
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26	Sun et al.	2017	the concept of “urban symbiosis” explores the synergistic effects between urban and industrial sectors by leveraging urban waste materials for manufacturing districts and considering industry as a provider of living resources.	Reduce, Reuse, Recycle, Recover, Rethink, Repair, Refurbish, Remanufacture, Repurpose
27	Dong et al.	2016	Industrial cooperation denotes the beneficial interchange of materials, energy, and/or by-products among neighboring industries through closed-loop systems. Urban symbiosis refers to the specific opportunities that arise due to the geographical proximity of cities and industrial areas. It can innovatively promote the local industry's use of urban waste to minimize ecological impact. Within this framework, waste disposal and economic growth can be cooperatively linked, thereby reducing resource utilization and pollutant generation.	Reduce; Reuse; Recycle; Recover ; Repair ; Refurbish; Remanufacture; Repurpose
28	Huang et al.	2015	The urban area represents a multifaceted superorganism, possessing a series of metabolic activities. Resources that are either obtained internally or sourced from the external supply will convert into material assets through a range of economic and social processes, with the remainder discharged into the environment.	Reduce; Reuse; Repurpose; Remanufacture; Recycle; Recover; Repair; Refurbish

29	Li et al.	2015	Industrial symbiosis enhances the utilization rate of resources (such as materials, energy, water, etc.) through closed-loop systems, which includes material/waste recycling and heat exchange. In particular, certain urban waste can be recycled by local industrial enterprises. Conversely, industries have the capacity to provide essential services to the city, such as heat energy. Under this concept, the city and industry can be harmoniously connected, thereby reducing resource consumption and pollutant emissions.	Rethink ; Reduce ; Recycle ; Recover ; Reuse ; Repurpose ;
30	Ma et al.	2014	The CE represents a model of sustainable development dedicated to environmental protection and pollution control, underpinning the pursuit of sustainable economic growth.	Reduce; Reuse; Recycle

Table A2. Indicators for Comprehensive Urban Development

No	Indicator	CE Principles	SDGs Goals Involved	Dimension
1	GDP (Gross Domestic Product)	Reduce; Rethink; Refuse; Recycle; Remanufacture; Repurpose; Repair; Refurbish	SDG 8	Economic
2	Population	Reduce; Reuse; Recycle; Recover; Repair; Refurbish; Remanufacture; Repurpose	SDG 3	Social
3	Resource Tax Revenue	Reduce; Rethink; Recycle; Recover; Refuse; Recycle; Remanufacture; Repurpose; Repair; Refurbish	SDG 17	/
4	Gas Waste Emissions and Removal	Reduce; Rethink; Repair; Refurbish; Remanufacture; Recycle; Recover; Refuse; Repurpose	SDG9; SDG12	Environment
5	Solid Waste Generation and Reuse	Reduce; Reuse; Recycle; Repurpose; Recover; Refuse; Repair; Refurbish; Remanufacture	SDG 11; SDG12	Environment
6	Wastewater Emission and Treatment	Reduce; Rethink; Recycle; Recover; Refuse; Repair; Refurbish; Remanufacture; Repurpose	SDG 6; SDG13	Environment
7	Environmental Pollution Treatment Facilities	Reduce; Rethink; Recycle; Recover; Refuse; Repair; Refurbish; Remanufacture; Repurpose	SDG 6; SDG11	Environment

8	Number of Employees in Manufacturing	Rethink; Reduce; Repair; Refurbish; Remanufacture; Repurpose; Recycle; Recover	SDG8; SDG 9	Economic
9	Number of Days with Good Air Quality	Reduce, Rethink, Recycle, Recover, Refuse, Repair, Refurbish, Remanufacture, Repurpose	SDG 3; SDG11	Social and Environment
No	Indicator	CE Principles	SDGs Goals Involved	Dimension
10	Number of Industrial Enterprises	Reduce, Rethink, Repair, Refurbish, Remanufacture, Recycle, Recover, Repurpose, Reuse	SDG8; SDG 9	Economic
11	Water Resource Supply and Consumption	Rethink; Reduce; Refuse; Reuse; Recycle; Recover	SDG 6	Environment
12	Green Coverage Rate	Rethink; Reduce; Reuse; Repurpose; Recover; Refuse	SDG11; SDG 15	Environment
13	Arable Land Area	Reduce; Rethink; Repair; Repurpose; Recycle; Recover; Refuse	SDG 2	Social
14	Resource Productivity Efficiency	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover; Remanufacture	SDG 12	Economic and Environment
15	Proportion of R&D in GDP	Rethink; Reduce; Repurpose; Remanufacture; Recover; Repair; Refurbish; Reuse; Refuse	SDG8; SDG 9	Economic

16	Added Value of High-tech Industry	Reduce; Rethink; Repair; Repurpose; Recycle; Recover; Refuse	SDG 9	Economic
17	Pesticide, Fertilizer Use Intensity	Reduce; Rethink; Refuse; Repair; Repurpose; Recycle	SDG 2; SDG12	Social and Environment
18	Municipal Waste Emission and Disposal	Reduce; Rethink; Reuse; Recycle; Recover; Refuse; Repair; Refurbish; Remanufacture; Repurpose	SDG 6; SDG 11	Environment
19	Health Investment	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover; Remanufacture	SDG 3	Social
No	Indicator	CE Principles	SDGs Goals Involved	Dimension
20	Treatment Capacity of Medical Waste	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover; Refuse	SDG 3	Social
21	Environmental Protection Expenditure	Rethink; Reduce; Repair; Refurbish; Repurpose; Recycle; Recover; Refuse; Remanufacture	SDG 13	Environment
22	Rate of Rural Sanitary Toilets	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover	SDG6; SDG3	Social and Environment
23	Emergy Economic Return Ratio	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover; Remanufacture; Reuse	SDG7; SDG 9	Economic and Environment

24	Energy Supply and Consumption	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover; Remanufacture	SDG7	Environment
25	Material Recycling	Reduce; Reuse; Recycle; Recover	SDG6; SDG7	Environment
26	Water-saving Irrigation Area Ratio	Reduce; Rethink; Reuse; Recycle; Refuse	SDG 6; SDG12	Economic and Environment
27	Per Capita Energy	Reduce; Rethink; Repair; Refurbish; Repurpose; Recycle; Recover	SDG 7: SDG 12	Economic and Environment

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