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Measuring circularity potential for medical waste management – a dynamic circularity performance analysis

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Abstract

The global transition towards circular economy (CE) signifies a shift in industrial waste management objective from "expansion of recycling industry" to achieve "waste as resource". The medical industry has attracted CE research attention the due to its significant waste generation and relatively slower progress towards CE, despite the substantial recycling potential identified by the WHO. Studies indicate that this can be attributed to the hazardous nature of medical waste and the prioritization of safety in waste treatment over potential economic and health co-benefits.

Recognizing the limitations of current waste management performance evaluation framework, this research introduces the dynamic circularity performance index, and further introduces the two new indicators of "recycling circularity (Rc)" and "real circularity performance", in conjunction with "recycling rate", to enable industry-specific sustainability assessment of waste management performance.

The case study on Taiwan medical waste management performance from 2014 to 2021 on the four identified medical waste categories confirms the limitations of assessing performance solely based on the quantity-based metric of "recycling rate". For example, the significant decline in the recycling rate from 33.1% to only 12.2% between 2019 and 2020 might be interpreted as a drop in environmental performance. However, the increase in both overall recycling efficiency and total volume of waste recycled, as demonstrated by "circularity performance" and "real circularity performance" reveals a well-maintained resource recovery performance in coping with the stunning 327% increase in total waste generation caused by the COVID-19 pandemic. Similarly, while the "recyclable waste' category exhibits a significant increasing in the recycling rate over the assessment period, the "Rc" results highlight a degradation in recycling efficiency.

The synergistic effect of the newly introduced indicators unveils several unique phenomena affecting the CE transition of the medical industry. These includes regulatory control, the single-use mindset, hazardous nature of the waste, the classification of waste, policy incentives and recycling capacity.

Further improvement can be made to expand the coverage to all life cycle stages and refine the method for determining the relative circularity of treatment performance. Such advancements can attribute to enhance waste management performance assessment and the development of effective CE transition strategies and policies.

Keywords Circular economy, Medical waste, Sustainability, Waste management, Dynamic circularity performance index, Performance assessment

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1 Introduction

The circular economy (CE) model has gained significant recognition for its potential contributions in terms of economic benefit [1], sustainability [2] and reducing primary resource extraction [3]. It has been widely embraced in industrial waste management (WM) as a solution to the challenges posed by the prevailing linear "take-make-waste" economic model [4–6]. However, despite its potential, the medical industry has been less actively engaged in the discourse and implementation of CE transition compared to other industries, such as food, plastic and manufacturing, due to the medical industry's inclination towards single-use practices, given the infectious, toxic and hazardous nature of medical waste [7].

In the past decade, the medical industry has experienced significant growth, leading to a substantial increase in the general of medical waste [8]. The issue is exacerbated by the unexpected COVID-19 pandemic with estimated increase in COVID-19 related medical waste of 3.4 kg cap^{-1} d^{-1} worldwide. The infectious nature of COVID-19 related waste resulted in the decline in recycling rate. Take Taiwan as example, the recycling rate of medical waste significantly decline from 33.1% to only 12.2% between 2019 and 2020. The terms "medical waste" and "healthcare waste" are used interchangeably [9]. In this study, "medical waste refers to all waste generated by healthcare activities and related sources, including hospitals, clinics, nursing homes for elderly, animal research and testing laboratories, blood bank and collection services and biomedical research centres and laboratories [10]. It is estimated that approximately 10% to 25% of medical waste is classified as "hazardous" and may pose a variety of environmental and health risk. The remaining 75 to 90% of the medical waste is non-hazardous and can be readily recycled [11]. However, due to its toxic, infectious and hazardous nature, medical waste has raised significant concerns regarding environmental impact, health implication, and overall well-being [12] and requires more sustainable and safe management practices.

The CE transition for medical WM has received significant policy support. The European Environment and Health Process roadmap [13] recognizes the CE transition as a guiding framework and highlights the benefit of applying waste hierarchy to prevent adverse environmental and health effects, as well as addressing cost and inequality issues related to WM [7, 13]. However, despite this policy level backing and the potential for high recycling rates, the single-use mindset in the medical industry poses a challenge to the CE transition. For instance, many European public health agencies and national governments still consider incineration as the only safe solution for hospital's waste treatment, despite evidence of its negative health and environmental impact [7] due to the considerable carbon footprint and production of air pollutant, carcinogens and harmful gases.

Extensive research has been conducted in the field of medical WM over the past decade, focusing on topics such as appropriate treatment methods for safe disposal [12, 14, 15], sustainability management of medical waste [16] and the development of indicators for medical WM [17, 18]. Studies on the CE transition of the medical industry suggest the need for further research in the areas such as the redesigning of circular healthcare practice [19], smart industry 4.0 enabled medical waste disposal system [12] and developing CE indicator for the healthcare industry to adequately measure and monitor the progress of medical waste management strategies [7].

Various studies have emphasized the importance of measuring and monitoring progress in the transition towards a CE [20–22], leading to an increasing focus on CE indicators [22–25]. At research level, CE evaluation is commonly performed using environmental assessment tools such as life cycle assessment, material flow analysis, multi-criteria decision tools [26, 27]. However, the comprehensive data required for these methods are often lacking [28]. As a result, in practice "recycling rate" has been extensively used as WM performance indicator. Recently, the benchmarking method [29–31] has gained popularity as tool for WM assessment.

The CE serves as a guiding principle that requires customized implementation strategies based on the unique characteristics of the target sector, which can be obtained through long-term and effective monitoring and evaluation. Reviews of current WM performance evaluation practices reveals gaps in assessing industry specific WM performance over time, particularly in the areas of "indicator of choice", "assessment criteria", "application level", industry specific focus" and "time-series analysis".

Among the indicators used, "recycling rate" emerges as the predominant WM performance indicator [32–40], despite studies indicating its inadequacy in measuring CE [41, 42]. This indicator lacks the ability to assess the linkage between CE and sustainability [43], waste management efficiency [44] and the complexities of multiple cycles and the consequences of down cycling [24]. As a result, several WM related assessment indices have been developed [22], including the circular economy index [24] for measuring circularity of a product, using longevity as measure of resource utilization [45], the material circularity indicator for assessing the "degree of circularity" in product materials [46], the waste hierarchy index for evaluating the WM compliance to the waste hierarchy concept [47] and the Circularity Performance Index (CPI) for integrated assessment from environmental, economic and social perspectives, which can be applied at different levels using typical WM data [48].

Regarding the "assessment criteria" and "application level", CPI is the only assessment framework capable of performing WM sustainability assessment at the industry level. CPI addressed the limitation of "recycling rate" by quantifying the recycling efficiency of waste treatment processes. However, none of the aforementioned assessment frameworks have been designed to perform industry-specific sector analysis over time.

Assessing the CE transition of the medical industry, requires obtaining industry-specific insights, considering the heavy regulatory control due to the toxic, infectious and hazardous nature of the waste generated. However, current WM assessment methodologies treat waste as homogeneous and do not distinguish waste according to its characteristic, resulting in proving only general overview instead of industry-specific insights. Additionally, existing WM performance evaluation matrices are static in nature, capturing performance at a specific instance. To interpret the transition, it is necessary to compare performance across different times, which is typically done by establishing a reference benchmark to eliminate the influence of external factors.

Given the challenges and issues in assessing the CE transition, this research aims to address two primary research questions (RQs).

> RQ 1: What are the gaps in practical assessment of CE transition in medical waste management over a period of time?
> RQ2: How to establish a practical WM performance assessment framework overcome the identified gaps?

This research has several objectives: (1) identifying solutions for performing industry specific assessment and analyzing chronological performance result; (2) modifying the existing CPI framework to accommodate the unique characteristics of the medical industry; (3) performing an approximate calculation with current waste generation and treatment data; and (4) providing insight into the waste management performance of medical industry.

2 Material and methods

2.1 Research framework

The objective of this research is to develop a WM performance evaluation framework that can provide the necessary insights for formulating CE strategies and policies specifically tailored to the medical industry. To achieve this objective, the research employed an iterative approach to establish the "Dynamic CPI (DCPI)". The DCPI framework possesses several capabilities, including integrated sustainability assessment; medical industry-specific assessment; assessment over a defined period of time and the utilization of general waste statistics without the need for additional research.

To validate the effectiveness of the proposed methodology, local medical waste management data from the period between 2014 to 2021 are utilized as a case study. The analysis of the data is followed by discussion of the findings in comparison to the existing literature. The research framework is schematically represented in Fig. 1.

2.2 The DCPI concept

2.2.1 The general DCPI concept

The waste management system development stage concept describes the transition of WM towards CE by shifting the goal from "expansion the recycling industry" to "waste as a resource". Similarly, the CPI interpreted the same phenomenon in the context of performance assessment, defining the CE transition as the expansion beyond the one-dimensional goal of optimizing recycling rate to include the additional dimension of optimizing the efficiency of the resource recovery process. This transition is as illustrated in Fig. 2a.

In the conventional recycling-oriented waste management system, industrial wastes are typically categorized as either recycled or non-recycled. The primary

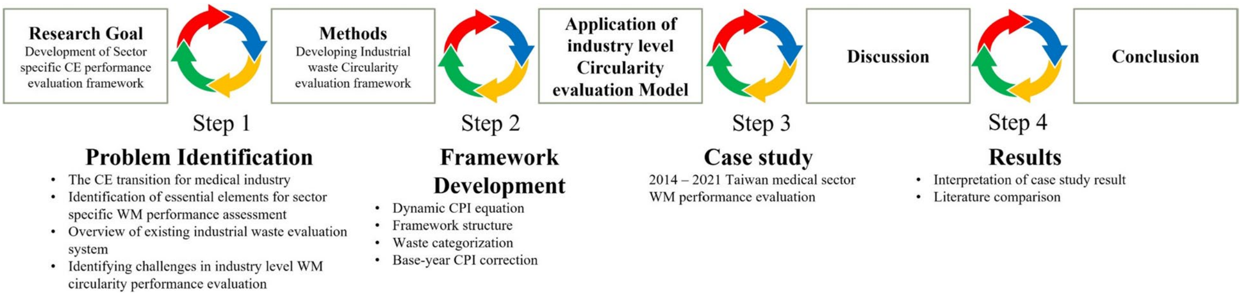
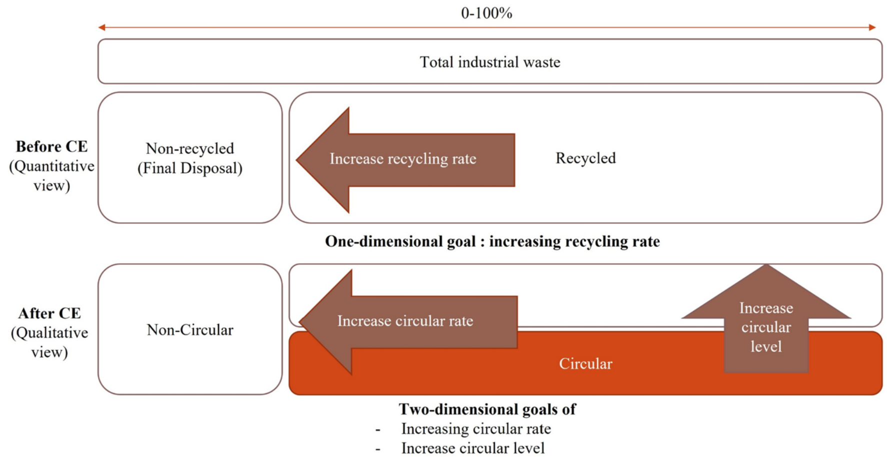
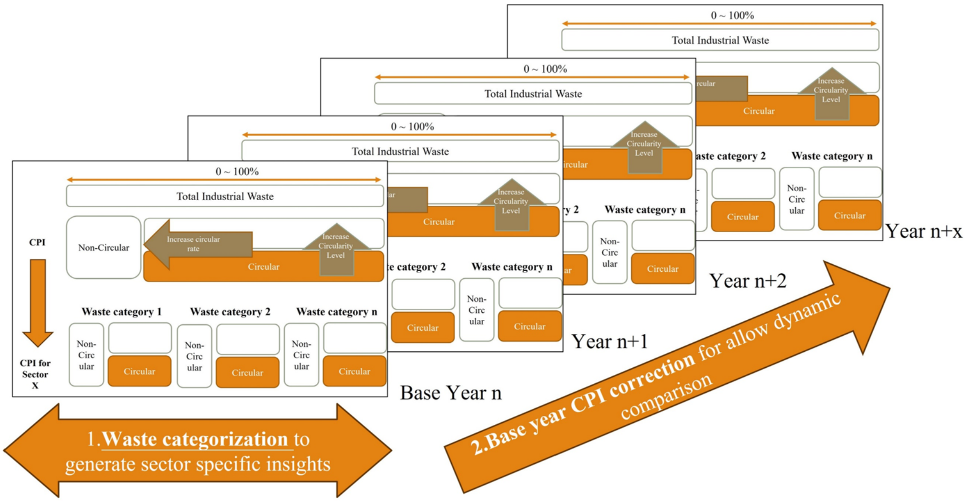


Fig. 1 Research Framework



(a) circularity performance index (CPI) concept [48]



(b) dynamic circularity performance index (DCPI) concept

Fig. 2 Schematic illustration of two concepts used in this study

sustainability objective in this context is to achieve a high recycling rate, which is calculated based on the quantity of waste entering recycling streams, without considering the quality or efficiency of the resource recovery process. However, the transition towards a CE entails a departure from the traditional environmental-centric WM mindset and emphasizes the pursuit of economic and social co-benefits through the optimization of resource productivity. In light of this transition, the CPI concept categorizes industrial wastes into recycled and non-recycled with two-dimensional sustainability preferences of optimizing both recycling rate and Rc. The recycling rate refers to the extent to which the waste materials are kept within the circular loops, while Rc measures the effectiveness of the resource recovery process.

Figure 2b shows the development from the original CPI concept to the DCPI to allow evaluation of industry-specific development trend in waste management performance by means of "waste characterization" and "base-year correction factor". "Waste characterization" entails the systematic classification of the generated waste by considering the distinctive characteristics exhibited by the waste produced within the specific industry of interest. This allows identification of industry-specific patterns and trends arising from the unique attributes inherent in the waste composition.

2.2.2 DCPI calculation procedure

The DCPI evaluation framework consists of four stages: (1) scoping: (2) data collection and compilation: (3) calculation; and (4) evaluation". A schematic representation of the proposed framework is presented in Fig. 3.

The scoping stage establishes the spatial and temporal boundaries of the system under study. In the "data collection and compilation" stage, the necessary waste statistics are gathered, including information on waste generation source, waste class, weight, and respective treatment methods. The calculation stage involves several preparatory tasks, such as "waste characterization", to identify the major waste categories, and "circularity level (CL) determination" achieved by pairing the recycling process inventory with the circularity classification (Supplementary Material (SM) Text-A1.

DCPI defined by two basic equations as:

$$\text{Circularity performance}(\text{Cp}) = \text{Recycling rate}(\text{Rr})^{*}\text{Rc} \tag{1}$$

Rr: the ratio of industrial waste recycled to total waste generated, calculated by dividing the weight of the recycled industrial waste by the weight of the total waste generated.

Rc: the average relative CL of the waste recycling process, calculated by dividing the cumulative CL by the CL of the waste generated.

C Frefers to the ratio of waste generation in the assessment year to the base year.

The CL concept is introduced as the means to quantify recycling circularity. This concept refers to the classification of recycling processes in terms of the relative sustainability and is established through the integration of key circular economy criteria and the sustainability preferences in the SM Text-A2.

Subsequently, calculation of "Rr", "Rc", "Cp" and "Dynamic Cp" can be performed using the collected industrial waste statistics. The full definitions and equations are presented in SM Text-A3.

$$\text{Dynamic Circularity performance}(\text{DCP}) = \text{CP}^{*}\text{Base Year Correction Factor}(\text{CF}) \tag{2}$$

Cp: the overall circularity for industrial waste management from a sustainability perspective, calculated as the product of the recycling rate and Rc.

The introduction of the "base-year CPI correction" component is intended to facilitate the comparison of the chronological CPI performance. While original CPI offers

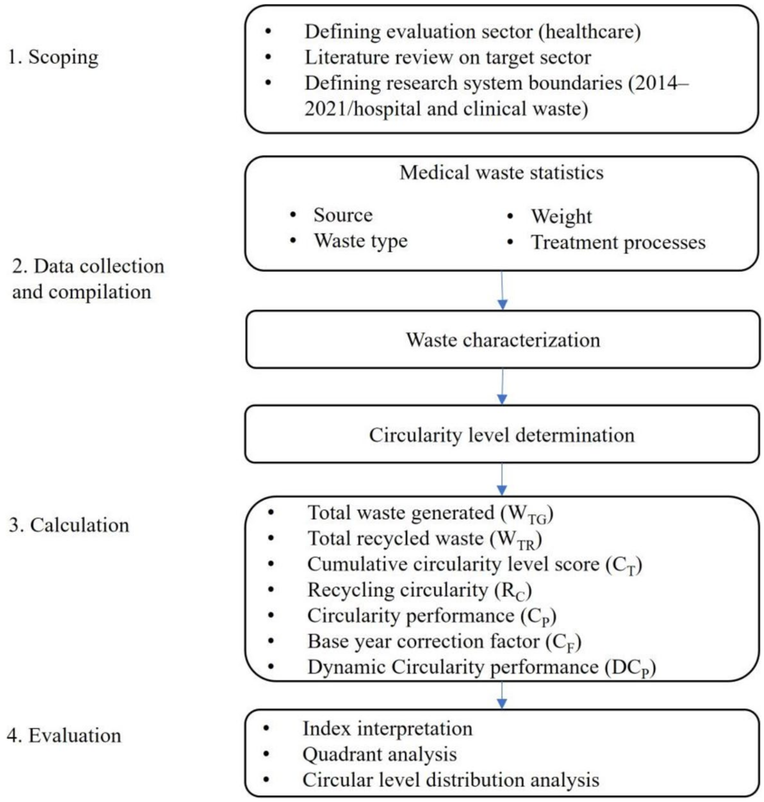


Fig. 3 The circularity performance evaluation framework

a static measure of performance at the specific point in time, allowing cross-industry comparisons within the same assessment year, it has been observed that directly comparing CPI results across different assessment year can result in misinterpretation, particularly when there are significant fluctuations in total waste generation. To address this issue, a base-year is selected as a reference benchmark and the "base-year correction factor" is calculated based on the ratio of total waste generation to the base-year. This correction factor is then utilized to convert nominal CPI values to real CPI value, ensuring more accurate and meaningful comparisons over time.

The evaluation stage employs "quadrant analysis" and "circularity class distribution" diagrams to provide a clear visual overview of the result.

2.2.3 Case study: 2014–2021 Taiwanese medical (hospital and clinical) waste

The Taiwan Environmental Protection Administration (TEPA) maintains an industrial waste reporting and management system, which contains comprehensive waste generation and recycling data. On the other hand, Taiwan has successfully transformed from the "garbage island" in the early 1980s to one of the global waste management leaders with 96.86% of waste properly disposed and a high recycling rate of 62.81%. In December 2018, the government announced the national CE promotion plan, marked the official transition towards a CE and making Taiwan a suitable case study for the transition from a recycling-based economy to a CE.

2.2.4 System boundary

The scope of this study is on the medical waste generated by hospitals and clinics in Taiwan from 2014 to 2021. The system boundary is defined to encompass the "WM" stage as defined by European Union's monitoring framework for CE. Detail information can be found in SM Text-B.

2.2.5 Medical waste data (2014–2021)

For this study, waste generation data from hospitals and clinics in Taiwan between 2014 and 2021, amounting to a total of approximately 707 kt was used. The waste generated encompassed 121 different types, and a variety of 26 treatment methods were employed. Additional information can be found in SM, such as industry classification and sector codes (Text-C) and Taiwan EPA codes for recycling and reuse processes (Table S4).

2.2.6 Medical waste characterization

The circularity potential of industrial waste is significantly influenced by the specific characteristics of the waste generated, which can vary across different sectors. In the case of medical waste, studies have highlighted the impact of its toxic, infectious and hazardous nature on the relatively slow CE transition, despite the presence of a high percentage of non-hazardous and potentially recyclable medical wastes. The Taiwan "waste disposal act" classifies industrial waste into "hazardous industrial waste" and "general industrial waste". Hazardous industrial waste refers to the waste produced by industry that is toxic or dangerous with the concentration or quantity sufficient to affect human health or the environmental. General industrial waste refers to waste produced by industry that is not hazardous industrial waste. For the purpose of this study, medical waste is classified into the 4 categories of "hazardous industrial waste", "biomedical waste", "general industrial waste' and "recyclable waste", based on TEPA's waste codes. A complete definition of each category and the respective waste codes can be found in the SM Text-D and Table S4.

2.2.7 CL determination

The CL represents the classification of recycling processes based on their relative sustainability. Recycling processes demonstrating higher resource efficiency, economic value and social benefits are assigned with a higher CL. For instance, recycling for resource recovery as raw material has a higher CL than recycling for energy recovery. The system is formulated using the following steps. More details can be found in SM Text-A.

> Step 1: Identification of CE criteria and sustainability preferences for industrial waste management. CE definitions were recategorized into environmental, economic and social perspectives.
> Step 2: Establishment of circularity classification criteria for industrial waste management. The circularity classification is formulated based on the key CE factors and preferences. It incorporates the waste hierarchy concept which prioritizes recycling processes in the order of (1) returned to the original resource, (2) derived product, (3) energy source and (4) returned to the biosphere. These categories are further refined by considering economic (change in value) and social (longevity) factors, resulting in the formulation of the circularity classification.
> Step 3: Development of the procedure to quantify Rc. The relative CL concept is introduced to quantify Rc. The list of parameters used to calculate Rc and circularity performance can be found in SM Text-A3.

3 Results

The CLs used for evaluation in this research were determined by pairing the "classification of circularity" (SM Text-A) with the inventory of recycling processes (SM Table S4). The 16 recycling processes in the waste statistics matched seven out of nine circularity classes, and the result is shown in Table 1. Additional information on the recycling cost and the state of the material when it is being recycled are needed to further pair the recycling processes to the two remaining circularity classes (SM Text-E and Table S6).

3.1 Results interpretation

Interpretation of the result is performed using a set of table and diagrams as introduced below.

3.2 General result

Table 2 below shows the calculated result for "Rr", "Rc", "Cp" and "DCp" for all medical waste categories. The calculations were performed using the definitions and equations provided in SM Text A-3. To facilitate data interpretation, the results are normalized and presented as percentages. It is important to note that the circular level concept pertains to the relative sustainability of the recycling processes, and the numerical values of "Rc" represent relative recycling efficiency within the sector, rather than absolute values.

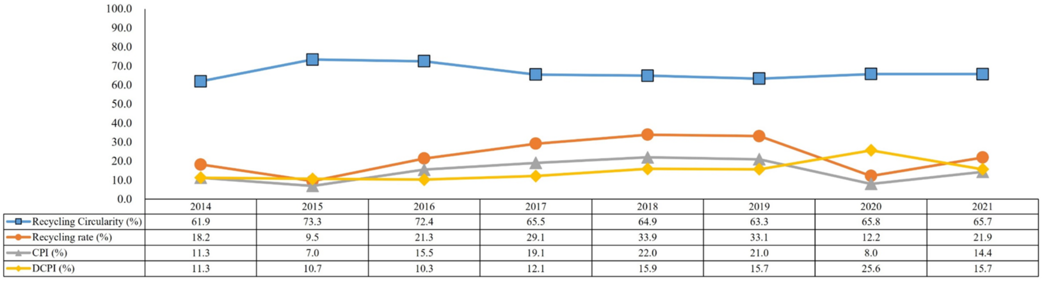
The Fig. 4a to e illustrate the performance trends of the four performance indicators from 2014–2021 in the order of total medical waste, hazardous industrial waste, biomedical waste, general waste and recyclable waste. The detail explanation of the results can be found in Sect. 3.2.

Table 1 List of the circularity levels used in the case study

Circularity level (CL)	Definition
CL7	Unlimited recycling as raw material in original form
CL6	Multiple recycling as raw material in original form
	Multiple recycling as raw material in different forms
	Multiple recycling as raw materials in different forms with a higher market value (upcycling)
CL5	Single recycling as additives of other products
CL4	Single recycling as an energy source with no potential to be reused and a negative market value
CL3	Single recycling returned to the biosphere with no potential to be reused and a negative market value
CL2	Direct return to the biosphere without treatment and a negative market value
CL1	Single recycling as an energy source with no potential to be reused and a negative market value

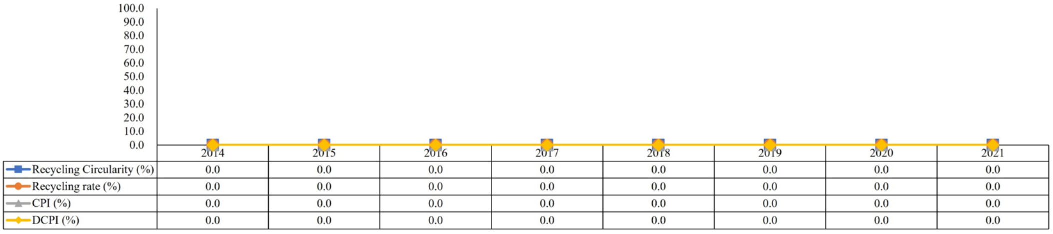
Table 2 Full result on recycling rate, recycling circularity, circularity performance and real circularity performance

		2014	2015	2016	2017	2018	2019	2020	2021	Average
Total Medical Waste	Recycling Rate (%)	18.2	9.5	21.4	29.1	33.9	33.1	12.2	21.9	22.4
	Recycling Circularity (%)	61.9	73.3	72.0	65.5	64.9	63.3	65.8	65.7	76.1
	Circularity Performance (%)	11.3	7.0	15.5	19.1	22.0	21.0	8.0	14.4	16.9
	Real Circularity performance (%)	11.3	10.7	10.3	12.1	15.9	15.7	25.6	15.7	16.6
Biomedical Waste	Recycling Rate (%)	12.5	9.2	21.8	23.6	29.3	24.6	8.6	17.8	18.4
	Recycling Circularity (%)	71.9	72.8	72.2	72.4	72.3	72.0	72.6	71.7	82.5
	Circularity Performance (%)	9.0	6.7	15.7	17.1	21.2	17.7	6.3	12.8	15.2
	Real Circularity performance (%)	9.0	12.7	11.7	11.5	16.2	14.4	27.3	15.4	16.9
Hazardous Waste	Recycling Rate (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Recycling Circularity (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Circularity Performance (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Real Circularity performance (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
General Waste	Recycling Rate (%)	0.4	0.1	0.11	0.2	0.2	0.2	0.1	0.1	0.2
	Recycling Circularity (%)	17.4	43.2	40.7	38.5	42.5	41.7	42.2	46.8	44.7
	Circularity Performance (%)	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1
	Real Circularity performance (%)	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.1
Recyclable Waste	Recycling Rate (%)	50.6	86.0	83.1	90.5	92.0	97.1	96.7	95.5	86.4
	Recycling Circularity (%)	53.6	75.6	73.4	56.1	53.0	53.1	53.3	56.5	67.8
	Circularity Performance (%)	27.1	65.0	61.0	50.7	48.8	51.6	51.6	54.0	58.5
	Real Circularity performance (%)	27.1	11.3	12.6	22.8	25.9	31.3	38.2	27.7	28.1



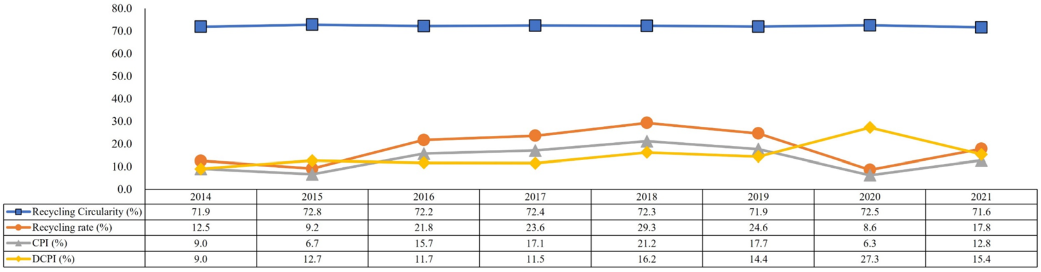
	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity (%)	61.9	73.3	72.4	65.5	64.9	63.3	65.8	65.7
Recycling rate (%)	18.2	9.5	21.3	29.1	33.9	33.1	12.2	21.9
CPI (%)	11.3	7.0	15.5	19.1	22.0	21.0	8.0	14.4
DCPI (%)	11.3	10.7	10.3	12.1	15.9	15.7	25.6	15.7

(a) Total Medical Waste



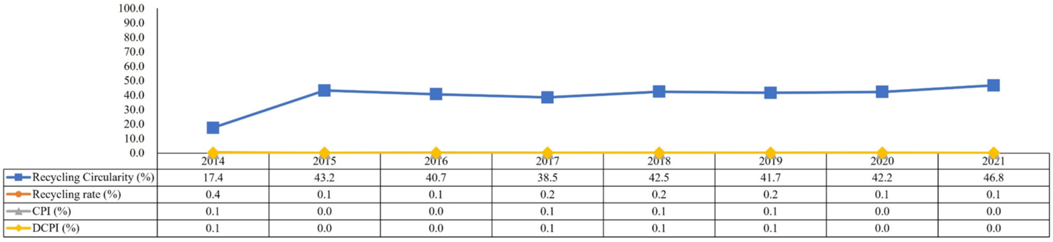
	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recycling rate (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CPI (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DCPI (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

(b) Hazardous Medical Waste



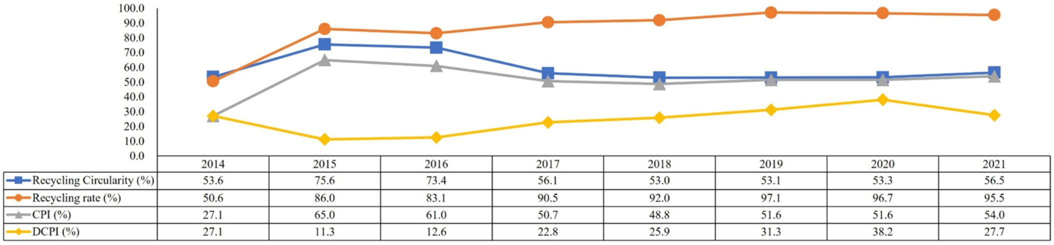
	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity (%)	71.9	72.8	72.2	72.4	72.3	71.9	72.5	71.6
Recycling rate (%)	12.5	9.2	21.8	23.6	29.3	24.6	8.6	17.8
CPI (%)	9.0	6.7	15.7	17.1	21.2	17.7	6.3	12.8
DCPI (%)	9.0	12.7	11.7	11.5	16.2	14.4	27.3	15.4

(c) Biomedical Waste



	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity (%)	17.4	43.2	40.7	38.5	42.5	41.7	42.2	46.8
Recycling rate (%)	0.4	0.1	0.1	0.2	0.2	0.2	0.1	0.1
CPI (%)	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0
DCPI (%)	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.0

(d) General Waste



	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity (%)	53.6	75.6	73.4	56.1	53.0	53.1	53.3	56.5
Recycling rate (%)	50.6	86.0	83.1	90.5	92.0	97.1	96.7	95.5
CPI (%)	27.1	65.0	61.0	50.7	48.8	51.6	51.6	54.0
DCPI (%)	27.1	11.3	12.6	22.8	25.9	31.3	38.2	27.7

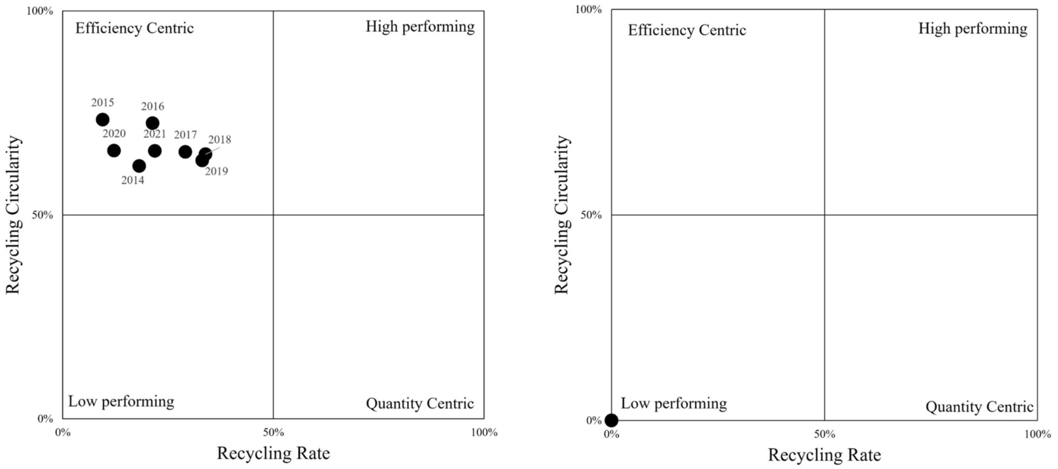
(e) Recyclable Waste

Fig. 4 DCPI results for different wastes

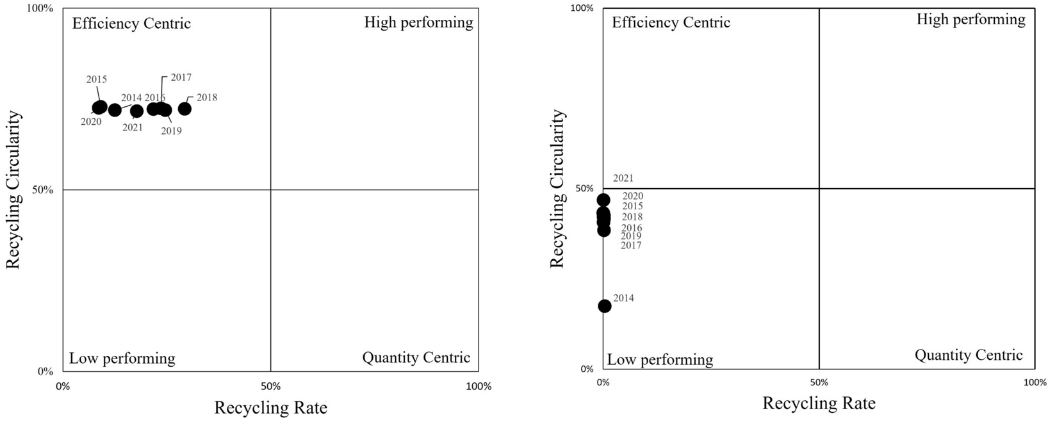
3.3 Quadrant analysis of "Rr" vs "Rc"

Figure 5a to e are the quadrant analysis diagrams for all waste types from 2014 to 2021. These diagrams aim to visually illustrate the circularity performance by both quantity (Rr) and quality (Rc) aspects. The diagrams are divided into four quadrants, each representing a distinct performance category.

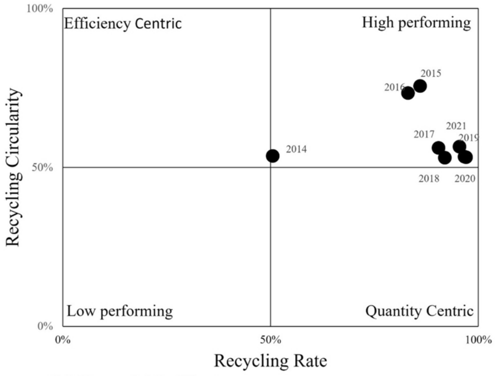
The top right quadrant is referred to as the "high performing" quadrant, indicating a high level of circularity performance in terms of both quantity (Rr) and quality (Rc).



(a) Total Medical Waste (b) Hazardous Medical Waste



(c) Biomedical Waste (d) General Waste



(e) Recyclable Waste

Fig. 5 Quadrant Analysis for different wastes

The top left quadrant is referred to as the "efficiency centric" quadrant, indicating a higher level of circularity performance in terms of the quality of recycling (Rc) compared to the quantity of recycling (Rr).

The bottom right quadrant is referred to as the "quantity centric" quadrant, indicating a higher level of circularity performance in terms of quantity (Rr) compared to the quality of recycling (Rc).

The bottom left quadrant is referred to as the “low performing” quadrant, indicating a low level of circularity performance in both quality (Rc) and quantity (Rr) of recycling.

3.4 CL distribution analysis

Figure 6a to e are the CL distribution diagrams of all medical waste categories. These diagrams provide a concise overview of the recycling circularity of each waste category. The values shown in the bars is the percentage of waste recycled through the particular circularity level shown in Table 1.

3.5 Key findings

3.5.1 Overall performance for total medical waste

Figure 4a presents three distinct performance trends observed, including low and fluctuating Rr, a consistently high and stable Rc, and gradual increase in the real CPI. The significant decrease in Rr in 2020 can be attributed to the stunning 327% increase in total medical waste generation from 55 kt in 2019 to 223 kt in 2020 during the beginning of the pandemic, which later returned to normal levels. Several factors influencing the WM performance are observed.

First, the high and stable Rc indicates the strict regulatory requirement that prevent the use of lower CL waste treatment processes. This is further supported by Fig. 5a, which shows the performance of total medical waste falling within the “efficiency centric” quadrant.

Second, the gradual increase in real CPI and the sharp decline in Rr suggest limited waste recycling waste capacity to handle the surge in waste generation. The correlation coefficient of -0.4852 between Rr and Rc over the 8-year period indicates a low negative correlation between these two indicators. The finding highlights the importance of using multiple indicators to accurately assess circularity performance.

3.5.2 Overall performance for hazardous medical waste

Hazardous medical waste accounts for less than 1% of total medical waste generation. As expected, all waste in this category is directly disposed of due to its hazardous nature. This reflects the stringent regulatory control over the management of hazardous waste. However, due to its relatively low percentage in the overall waste composition, the impact of hazardous waste on the overall circularity is minimal.

3.5.3 Overall performance for biomedical waste

Biomedical waste is the largest category of medical waste, account for an average of 76.6% of total medical waste generation from 2014 to 2021. The circularity performance trend for biomedical waste closely resembles the result for total medical waste generation, primarily due to its significant contribution. This highlighted the importance of waste characterization and evaluation each individual waste group separately. Failing to do would result in performance assessment reflecting only the characteristics of the waste group with the largest volume contribution to the total waste.

3.5.4 Overall performance for general medical waste

General medical waste constitutes the second largest group, accounting for 13.5% of the total waste generation. Figure 4d shows the combination of relative high circularity performance with extremely low Rr of between 0.06% to 0.39%. This is unexpected considering the non-hazardous nature of the waste and its recycling potential. Figure 5d indicates the overall performance lies in the “low performing” quadrant. The existing practice of incinerating non-hazardous medical waste may be influenced by the single-use mindset.

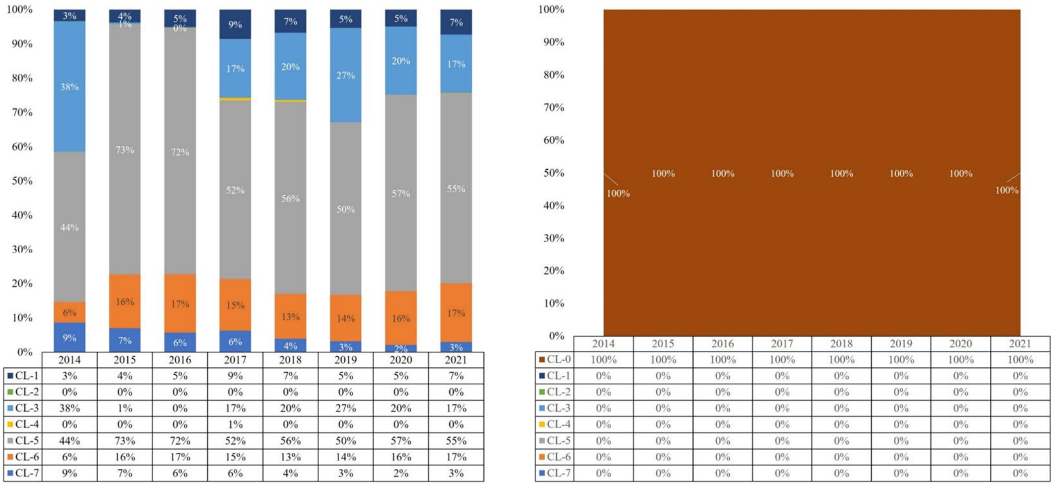
3.5.5 Overall performance for recyclable medical waste

Recyclable wastes are general wastes that have been designated by the authority for mandatory recycling due to the nature of the waste. The substantial and consistent increase in recycling from 50.6 to 95.5% over the 8-year period reflects a strong policy drive towards recycling waste under this category. However, the stagnant recycling circularity and real CPI indicate a focus primarily on the quantity rather than the quality of waste treatment during this period. Figure 6e shows the circularity performance falling within the “high performing” quadrant, aligning with the non-hazardous and highly recyclable nature of this waste category.

4 Discussion

4.1 Recycling rate as CE indicator for medical waste management

Several studies have pointed out the limitations of using “Rr” as a sole WM performance indicator, as it can potentially lead to misinterpretation. For instance, the Rr for total medical waste decreased from 21.0% in 2019 to 8.0% in 2020, suggesting a decline in performance.

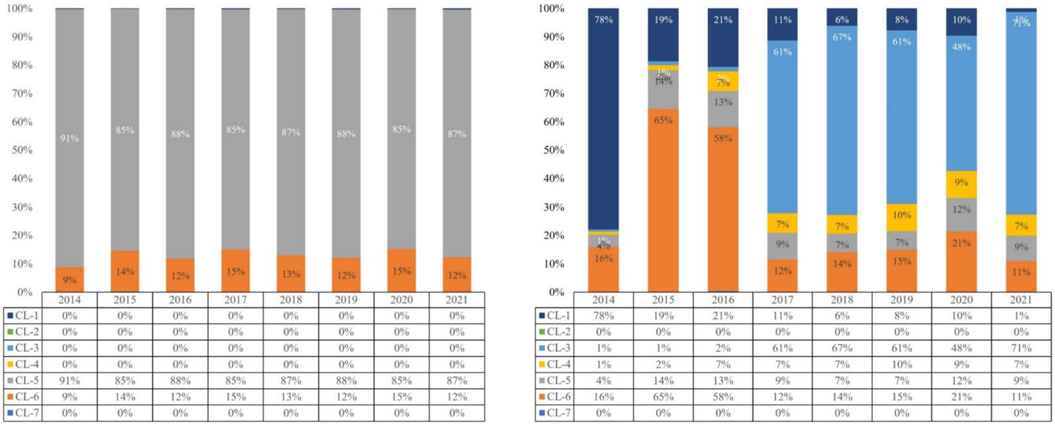


	2014	2015	2016	2017	2018	2019	2020	2021
■CL-1	3%	4%	5%	9%	7%	5%	5%	7%
■CL-2	0%	0%	0%	0%	0%	0%	0%	0%
■CL-3	38%	1%	0%	17%	20%	27%	20%	17%
■CL-4	0%	0%	0%	1%	0%	0%	0%	0%
■CL-5	44%	73%	72%	52%	56%	50%	57%	55%
■CL-6	6%	16%	17%	15%	13%	14%	16%	17%
■CL-7	9%	7%	6%	6%	4%	3%	2%	3%

(a) Total Medical Waste

	2014	2015	2016	2017	2018	2019	2020	2021
■CL-0	100%	100%	100%	100%	100%	100%	100%	100%
■CL-1	0%	0%	0%	0%	0%	0%	0%	0%
■CL-2	0%	0%	0%	0%	0%	0%	0%	0%
■CL-3	0%	0%	0%	0%	0%	0%	0%	0%
■CL-4	0%	0%	0%	0%	0%	0%	0%	0%
■CL-5	0%	0%	0%	0%	0%	0%	0%	0%
■CL-6	0%	0%	0%	0%	0%	0%	0%	0%
■CL-7	0%	0%	0%	0%	0%	0%	0%	0%

(b) Hazardous Medical Waste

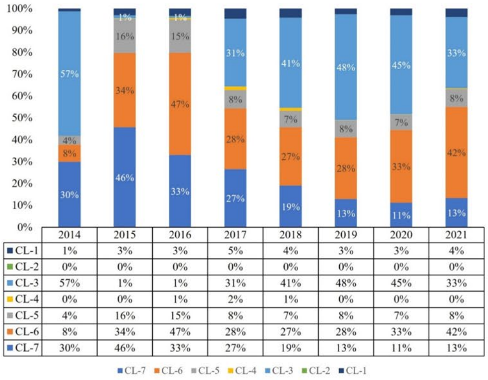


	2014	2015	2016	2017	2018	2019	2020	2021
■CL-1	0%	0%	0%	0%	0%	0%	0%	0%
■CL-2	0%	0%	0%	0%	0%	0%	0%	0%
■CL-3	0%	0%	0%	0%	0%	0%	0%	0%
■CL-4	0%	0%	0%	0%	0%	0%	0%	0%
■CL-5	91%	85%	88%	85%	87%	88%	85%	87%
■CL-6	9%	14%	12%	15%	13%	12%	15%	12%
■CL-7	0%	0%	0%	0%	0%	0%	0%	0%

(c) Biomedical Waste

	2014	2015	2016	2017	2018	2019	2020	2021
■CL-1	78%	19%	21%	11%	6%	8%	10%	1%
■CL-2	0%	0%	0%	0%	0%	0%	0%	0%
■CL-3	1%	1%	2%	61%	67%	61%	48%	71%
■CL-4	1%	2%	7%	7%	7%	10%	9%	7%
■CL-5	4%	14%	13%	9%	7%	7%	12%	9%
■CL-6	16%	65%	58%	12%	14%	15%	21%	11%
■CL-7	0%	0%	0%	0%	0%	0%	0%	0%

(d) General Waste



	2014	2015	2016	2017	2018	2019	2020	2021
■CL-1	1%	3%	3%	5%	4%	3%	3%	4%
■CL-2	0%	0%	0%	0%	0%	0%	0%	0%
■CL-3	57%	1%	1%	31%	41%	48%	45%	33%
■CL-4	0%	0%	1%	2%	1%	0%	0%	0%
■CL-5	4%	16%	15%	8%	7%	8%	7%	8%
■CL-6	8%	34%	47%	28%	27%	28%	33%	42%
■CL-7	30%	46%	33%	27%	19%	13%	11%	13%

(e) Recyclable Waste

Fig. 6 Circularity level distribution for different wastes

However, when considering the real CPI, it becomes evident that there was an actual increase in total volume of waste recycled. This indicates a potential limitation in the recycling capacity which resulted in a misleading decline in the Rr.

The performance of recyclable waste presents another scenario where relying on recycling as WM performance can be misleading. The significant increase in Rr over the 8-year period suggest overall improvement in sustainability. However, when examining the marginal improvement in Rc and the decline in real CPI, it becomes apparent that the focus has been primarily on increase the volume of recycling rather than improving the quality of recycling. This highlights the risk of assessing WM performance based solely on Rr. Simultaneously, it is evident that the introduction of the new indicators contributes to a better overall performance evaluation.

4.1.1 Application of "Rc" for measuring waste management performance

"Rc" represents the quality or efficiency aspect of the resource recovery process, serving as a complementary measure to the conventional assessment based solely on the "Rr", providing insights that are often overlooked when assessing solely on quantity-based evaluation.

The findings from the case study on Rc present a distinct outlook on the waste management practices that are not captured by "Rr". This is evident from the weak negative correlation coefficient observed between the numerical results of the two indicators. For instance, consider the results for the "recyclable waste" category. While a steady increase in the "Rr" might create a false impression of improved environmental performance, the simultaneous decline in "Rc" during the same period signifies a decrease in performance from a quality perspective. Similarly, the fluctuating "Rr" for total medical waste during the assessment period provides limited insights beyond the numerical value. Conversely, the consistently high and stable "Rc" over the same period indicates sustained efforts to maintain recycling quality.

The quadrant analysis diagram serves as a visual representation of the CPI results, offering a breakdown from both quantity (x-axis) and quality (y-axis) perspectives. This diagram effectively demonstrates the interpretation of "Rc" and visually highlights the unique characteristics of WM performance across the four waste categories.

" Rc" refers to the normalized average CL, enabling the identification of recycling "hotspots" across various waste categories based on the quality perspective, by means of the CL distribution chart.

4.1.2 Factors influencing the CE transition of medical industry

Studies have identified various factors influencing the adoption of CE practice in the medical industry. The factors include the hazardous nature of the medical waste, strict regulatory control and the single-use practice. The evaluation results from the case study not only align with these factors but also reveal the presence of additional influencing factors, such as policy drive, waste classification and recycling capacity.

The stringent regulatory control is evident in the consistent and relatively high Rc observed for most waste categories. However, the requirement over recycling through higher CL process is due to concerns over potential health risks rather than sustainability.

Single-use mindset is particularly noticeable in the case of general medical waste, which is non-hazardous and potentially recyclable. It is surprising to see almost all waste under the general medical waste category goes directly to incineration rather than recycling.

The hazardous nature of medical waste, particularly in the hazardous medical waste category results in direct disposal through incineration. However, since this category constitutes a small percentage of total waste generation, it has little impact on the overall circularity performance.

Policy plays a significant role in the significant increase in Rr for the recyclable waste category, despite only marginal improvement in terms of overall circularity. The mandatory recycling requirement under this category has driven the increase in Rr.

Waste classification is also an important factor to consider. The ratio of hazardous to non-hazardous waste from the case study differs significantly from the general figure provided by WHO. With the increasing real CPI for biomedical waste indicating a growing volume of waste being recycled, this raises speculation that a portion of the biomedical waste could be classified as non-hazardous. As previously shown that waste management practices are highly dependent on waste categories, more accurate classification of waste could improve the waste management performance.

Recycling capacity is an essential aspect of waste management. In 2020, the surge in total waste generation, along with the incremental growth in real CPI, suggests that the waste generation exceeded the existing recycling capacity, leading to a decline in the Rr.

4.1.3 Evaluation of medical waste by sub-categories

The case study result reveals the differences in WM performance among different waste categories within the medical sector due to the unique characteristic of each waste category. This finding underscores the importance of considering the unique characteristic of waste categories when formulating industry-specific circular economy strategy. It is important to note that performance evaluation result for total medical waste generation is relevant only to the biomedical waste category due to its large contribution to the total medical waste generation.

4.1.4 The practical application of dynamic analysis

The CPI was designed to assess and compare waste management performance at the national level and sectoral level within a given assessment year. However, since CPI is calculated based on the total waste generation of the assessment, adjustments are necessary to mitigate errors arising from the variations in annual waste generation. Comparison between CPI and DCPI result reveals improvements in performance, particular in interpreting the fluctuations in recycling rate during the assessment period.

4.2 Limitation of the study

The indicators developed in this research and the result from the case study have certain limitations. These limitations include:

> Scope: the case study focuses solely on the waste generated by hospitals and clinics, excluding waste from other related institutions or services, including laboratories and research centres; mortuary and autopsy centres; animal research and testing laboratories; blood banks and collection services.
>
> Waste classification: medical waste and by-products cover a diverse range of materials, including infectious waste, pathological waste; sharps waste; chemical waste; pharmaceutical waste; cytotoxic waste; radioactive waste; and non-hazardous or general waste. This research categories medical waste into the 4 general categories of "hazardous", "biomedical", "general" and "recyclable" in compliance to the local waste classification.
>
> Application condition: the assessment requires relatively comprehensive data coverage of the WM activities, which is typically from well-managed industrial waste management systems commonly found in developed countries. In case with limited existing waste management data, additional investigation may be required.
>
> Factors not considered: the assessment focused solely on the WM stage and did not include the waste collection, storage and transportation stages. As a result, it has not included the impact of factors such as transportation distance and variations in recycling process efficiency.

5 Conclusions

Proper management of industrial waste is essential for achieving a circular economy, necessitating an effect framework for monitoring and evaluating WM performance. Current review of public waste management evaluation practice reveals the dominant use of "Rr" as performance indicator despite studies indicating its inadequacy as CE indicator. In contrast, the medical industry has shown relatively slower CE transition compared to the food, plastic and manufacturing industries, due to the factors such as the hazardous nature of the waste, health and safety-based regulatory control and the singlet-use mindset. Moreover, the existing performance evaluation framework fails to provide the industry-specific insights necessary for formulating feasible CE transition strategies.

In response to the abovementioned challenges encountered in the assessment of practical industrial WM, this study developed the "DCPI" as a method to evaluate the current WM performance and the factors influencing the CE transition in the medical industry from 2014 to 2021.

The findings from the case study results hold several significant implications. First, it establishes the viability of measuring circularity of an industry by the "circularity performance" concept, which underscores the importance of evaluating the quality of recycling rather than merely focusing on the quantity. The outcomes of this investigation reconfirmed the limitation of "Rr" observed in the previous studies and showcase the advantage of employing multiple indicators for comprehensive assessment, Second, it is noteworthy that prior studies concerning WM performance were largely confined to addressing specific aspect of the sustainability spectrum. In contrast, this study successfully integrated key sustainability criteria used in previous studies, enabling a more holistic evaluation of sustainability through a quick and dirty manner using generic waste management data.

The case study demonstrated the effectiveness of the DCPI in assessing waste management performance and uncovering factors influencing the CE transition in the medical industry. Notably, significant differences were observed in the WM practices among the four major categories of medical waste, including "hazardous medical waste", "biomedical waste", "general waste" and "recyclable waste". This highlighted the need for waste category-level performance assessments to better inform CE strategies and policies. The identified factors influencing the CE transition align with the existing literature, including the hazardous nature of medical waste, single-use mindset and the health and safety based regulatory control. Additionally, new factors identified in this research includes policy incentive, waste categorization and recycling capacity are also shown in the research. These insights can contribute to the formulation and implementation of CE transition policy or strategy for medical industry.

Furthermore, the results also demonstrated the necessity of implementing data correction as a resolution to the errors encountered when assessing multiple year performance trends during significant fluctuation in the total waste generation, such as the COVID-19.

However, it is important to note that the assessments in this study are limited to the waste treatment stage and not covering the potential impacts during waste generation and transportation stages. Further improvement can be made to encompass the entire life cycle of medical waste and the methodology in determining recycling circularity. These developments have the potentials to enhance WM assessment and facilitate better formulation of CE transition strategy and policy.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-023-00188-5.

Additional file 1: Table S1. Classification of circularity. **Table S2.** Key CE factors and sustainability preferences. **Table S3.** Definitions and equations of parameters. **Table S4.** Treatment process codes. **Table S5.** Waste characterization result. **Table S6.** Circularity class pairing result.

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Authors' contributions

Chih-Kai Yang contributed to the design and implementation of the research, to the analysis of the result. Hwong-Wen Ma supervised the findings of this work. Mei-Hua Yuan contributed to the outline of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

All data generated or analyzed during this study are available upon request.

Declarations

Competing interests

The authors declare they have no competing interests.

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