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博士論文

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建構循環度績效指數分析廢棄物管理循環現況及潛力

Measuring circularity potential of waste management practice using the Circularity Performance Index

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摘要

循環經濟 (Circular Economy, CE) 的全球迅速普及，反映出生產體系積極擺脫「開採-製造-廢棄 (take-make-waste)」的線性經濟模式，而轉向追求資源效能及附加價值的最大化。從工業廢棄物管理的角度，這反映出從以提升回收率為主的「擴大回收產業」目標，轉型為追求永續資源循環，以達到「廢棄物為資源」的零廢棄目標。而有效的績效管理，是達到上述轉型所不可或缺的重要關鍵。

然而，文獻顯示既有工業廢棄物管理績效評估有諸多問題與挑戰，例如過度依賴「回收率」、缺乏具備全面性的永續評估模式、可供績效評估之廢棄物管理資料有限、無法提供產業的深入洞察、無法提供政策制定所要的發展趨勢、以及在不同時空尺度下的應用性等。

為解決上述問題，本研究提出了「循環度績效 (Circularity Performance)」的概念，用以評估工業廢棄物管理的循環經濟轉型。循環度績效主要基於下面的方程式

循環度績效(C_P) = 回收率(recycling rate, R) * 回收循環度 (recycling circularity, R_C)

上述方程式將工業廢棄物管理的循環度定義為數量 (回收率) 及品質 (回收循環度) 的綜效。新建立的指標「回收循環度」代表了廢棄物再利用的相關效率。其計算方式採用一般的工業廢棄物管理資料，透過新建立的「循環等級 (Circularity level)」概念，以廢棄物層級 (Waste Hierarchy)、價格及循環性 (loop)等三個面向進行環境、經濟及社會面相的優選後，將其量化。

本研究以「循環度績效」為基礎，建立了兩種不同的指數系統。「循環度績效指數（Circularity Performance Index, CPI）」主要用於定期的年度廢物管理績效評估，並可進行跨產業的績效比較。而「動態循環度績效指數（DCPI）」設計為以協助政策成效分析及制定為目標，可提供反映產業特性的較深入分析及時間序列的發展趨勢分析。

本研究透過兩個個案分析，針對兩個指數系統實際應用性的驗證。案例一以國內 27 個製造業部門為對象，進行 2021 年度廢棄物管理績效的評估，以示範其在國

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家和產業層級的適用性。結果顯示與過去僅以「回收率」做為評估指標的結果有很大的差異。「回收率」及「回收循環度」兩個指標的關聯性低，因此有高「回收率」的部門，由於低「回收循環度」而在整體「循環度績效」表現不佳。驗證了依賴「回收率」做為績效指標的局限性，同時強也反映出再利用效率對於整體循環度提升的重要性。此外，結果也反映出了部份影響廢棄物再利用決策的外部因素，例如廢棄物成分、費用、市場需求及處理技術可及性等。

案例二以國內醫療廢棄物為對象，以 DCPI 分析 2014 年至 2021 年的醫療廢棄物(僅包括醫院及診所)管理績效。結果也同樣反應出基於「回收率」進行績效評估的侷限性。例如 2019 年至 2020 年間，回收率由 33.12% 下跌至僅 12.2%，似乎反映出管理績效的下滑。然而，「回收循環度」及實質「循環度績效」顯示同期除了回收效率維持同等水平，其實際回收量也有所增加。也反映出在 COVID-19 造成的極端醫療廢棄物產量暴增 327%的情況下，不適合單以「回收率」作為績效指標。在「公告應回收或再利用廢棄物(R 類)」醫療廢棄物的評估結果顯示，該類別在評估期間的「回收率顯著增長」，但若納入「循環度績效」及「回收循環性」的考量，則會發現整體回收效率下跌的情形。除了從數據上反映出績效的變化，研究結果也顯示出了幾個影響醫療產業循環轉型的獨特現象，包括監管控制、一次性使用、廢棄物的危害性、廢棄物分類方式、政策誘因和回收量能。

本評估模式仍有許多可進一步發展之潛力，包括擴大廢棄物生命週期的涵蓋及改善「回收循環度」量化模式等。可提升工業廢棄物管理績效評估，以協助產業的循環轉型。

關鍵詞： 循環經濟、廢棄物管理、績效指標、循環度、永續發展

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Abstract

The rapid global adoption of the circular economy (CE) concept signifies a paradigm shift in the global production system, promoting a transition away from the linear "take-make-waste" model towards maximizing resource intensity and value addition. For industrial waste management, the transition has led to a shift from quantity driven concept focusing on "expansion of recycling industry" to the pursuit of optimal resource recovery quality through achieving "waste as resource". Existing literatures highlights various issues and challenges in the existing industrial WM performance assessment practice, such as the over dependance on the conventional indicator "recycling rate"; the lack of a holistic sustainability assessment approach; limited waste management data available for performance assessment; inability to provide industry-specific insights; limited ability to reveal development trends for policy formulation; and application challenges across spatial and temporal levels.

To address the aforementioned challenges, this research proposes the "circularity performance" concept for assessing the CE transition of waste management practice. The concept is based on a simple equation of

Circularity performance (Cp) = Recycling rate (R) * Recycling circularity (Rc)

This equation defines circularity performance for industrial waste management as the product of quantity (recycling rate) and quality (recycling circularity). The newly introduced indicator "recycling circularity" represents the relative recycling efficiency of waste recycling processes. Quantification of "recycling circularity" utilizes standard industrial waste management data is made possible through a novel approach named "circularity level" concept, which allows for integrated assessment from environmental, economic and social perspectives.

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Two index systems are established based on this concept. The Circularity Performance Index (CPI) is designed for regular annual WM performance assessment and enables inter-sectoral performance comparison. On the other hand, the Dynamic Circularity Performance Index (DCPI) is tailored to support policy formulation by providing industry-specific insights and development trend over a defined timeframe.

To demonstrate the feasibility of the two index systems, two case studies were conducted. The first case study assesses 27 manufacturing sectors in 2021 using the CPI to illustrate its applicability at national and sectoral levels. The result differs significantly from assessment using only "recycling rate" alone with sectors having high recycling rates performing poorly in overall CPI due to low recycling circularity, and vice versa. This outcome has several significant implications. The weak correlation between "recycling rate" and "recycling circularity" aligns with the observed limitation of assessing through "recycling rate" alone, while underscoring the importance of considering the quality of recycling process. In addition, the result reveals the potential impact of various factors influencing waste recycling decision, such as waste composition, cost, market demand and technology availability.

The second case study examines Taiwan's medical waste management performance from 2014 to 2021 using DCPI. Again, result shows the limitation of performance assessment by "recycling rate" alone. For example, the significant decline in the recycling rate from 33.12% to only 12.2% between 2019 and 2020 might be interpret as a decline in environmental performance. However, the increase in both overall recycling efficiency and total volume of waste recycled, as demonstrated by CPI and DCPI reveals a well-maintained resource recovery performance in coping with the surge in total waste generation caused by the COVID-19 pandemic. Similarly, while the "recyclable waste' category shows a

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significant improvement in "recycling rate" over the assessment period, the "recycling circularity" results highlight a degradation in recycling quality. The synergy between the newly introduced indicators reveals several unique phenomena influencing the CE transition of the medical industry, including 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 recycling circularity of treatment performance. Such advancements can enhance waste management performance assessment and contribute to the development of effective CE transition strategies and policies.

Keywords: circular economy, industrial waste management, circularity, sustainable development, performance indicator

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Chapter 1 Introduction

Recognized for its vital role in the transition towards a circular economy (CE), waste management has sparked a significant increase in related research, including performance indicators. However, a commonly recognized CE indicator for industrial waste management (WM) is still lacking, and the "recycling rate" remains the dominant performance indicator for assessing industrial WM. This chapter examines the evolution of industrial WM and its transition towards the circular economy, to identify the various challenges in industrial WM performance assessment practices. The results serve as the foundation for establishing the research goal, objectives, and structure of this study.

1.1 Evolution of waste management

Modern waste management can be tracked back to the 18^{th} century Industrial Revolution. The technological advancement not only contributed to the rapid economic growth and urbanization but also resulted in the significant increase in resource consumption and degradation of environmental quality. Incineration and sanitary landfills were introduced in the late 18^{th} century (Bevan, 1969) and remained the primary options for the treatment of industrial waste. In the 1970s, with increasing concerns over environmental pollution, the shortage of landfill space and resource conservation, environmental laws such as the National Environmental Policy Act (NEPA) (USEPA 1975), Resource Conservation and Recovery Act (RCRA) (USEPA, 1976), Solid Waste Disposal Act (USEPA, 1976), Toxic Substances Control Act (USEPA, 1976) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (USEPA, 1980) were introduced to protect environmental quality. Around the turn of the millennium, there was a significant shift towards the integration of environmental and economic benefits, with the Organisation for

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Economic Co-operation and Development (OECD) promoting "sustainable material management (SMM)" practices to stimulate resource circulation for both environmental and economic purposes (OECD, 2001). At the same time, the European Commission's Waste Framework Directive adopted the waste hierarchy as the guiding principle for waste management (EC, 2008), prioritizing waste prevention, waste minimization, preparation for reuse, recycling, other recovery methods and final disposal, to stimulate the integration of social and economic considerations in the formulation of the best practicable environmental options (Hansen, 2002). Since then, new policies for waste prevention, sustainable material management, integrated product policies and 3R (Reduce, Reuse, Recycle)-related policies have been launched worldwide (Auci, 2013).

However, the practice of linear "take-make-waste" economy model led to continuous degradation of environmental quality, depletion of natural resources and rapid climate change has urged led to the pursue of an alternative economic model for a more sustainable growth. The CE concept emerged as the new economic guiding principle for the recognized potential in achieving economic benefit (Lacy et al., 2015), sustainability (Lewandowski, 2016) and reducing primary resource extraction (Bianchi et al., 2023) through more efficient use of materials (Kirchherr et al. 2017; Saavedra et al. 2018). In the past decades, we have witnessed the evolution of environmental policy from the early end-of-pipe concept to the later pollution prevention (Nelles et al., 2016) and eventually the current adoption the CE concept. Research on new business models received much attention (Chen et al. 2020, Pieroni et al. 2021) as the driving force for maximizing value creation through minimization of resource consumptions (Schulte, 2013; Bocken et al., 2016; Lieder and Rashid, 2016). New WM policy requirements for traceability and operational transparency (Sahoo, Mukherjee, & Halder, 2021) stimulated the adoption of emerging technologies to significantly reduce waste

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generation (Aloui et al., 2023; Pal and Bhatia, 2023). Blockchain-based solutions, with its advantage in traceability and transparency, have been developed for optimizing waste management system (Castiglione et al., 2023), waste exchange platform (Ratnasabapathy et al., 2019), waste monitoring (Schmelz et al. 2019), decentralized waste database, (Soldatos et al., 2021), reward system (Akram, Alshamrani et al., 2021) and plastic waste management (Bhubalan et al., 2022). The influence of CE extends beyond national borders, as digitalization significantly impacts sustainable upgrading in global value chains (GVCs) (Awan et al., 2022). This leads to green growth in the manufacturing industry and contributes to the development of more environmentally sustainable production system (Qu et al., 2020), such as smart textile waste management system (Chowdhury et al., 2023).

1.2 The waste management transition towards a circularity economy

Circular Economy is an integration of several environmental concepts including industry ecology, cradle to cradle and performance economy (Kirchherr et al. 2017; Saavedra et al. 2018) to stimulate economic development through more efficient use of materials. Instead of focusing on technological improvement, CE calls for more innovative design in organizational and social aspects to influence the value chain (Vanner et al., 2014) and has been widely recognized for its potential economic benefit (Lacy et al., 2015) while moving towards sustainability (Lewandowski, 2016).

The popularity of the CE model is evidenced by the growing number of countries adopting CE as national policy. In March 2020, the European Commission adopted the "new circular economy action plan", aiming to reduce the pressure on natural resources while creating sustainable growth and jobs (EC, 2020). By 2021, 23 members of the United Nations Economic Commission for Europe (UNECE) had adopted the CE concept with new

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initiatives along the entire life cycle of products as the new economic model to achieve sustainable development (UNECE, 2021).

Waste management policy has been recognized for its vital role in the transition towards a CE (Bilitewski, 2012; Ranjbari et al., 2021). The adoption of CE concept signifies the shift of waste management policy goal from “expansion of the recycling society” to “waste as resource” (Campitelli et al., 2022) and calls for more innovative design in organizational and social aspects to influence the value chain (Vanner et al., 2014).

1.3 The current status and challenges in assessment circularity of waste management

The importance of measuring and monitoring progress towards a circular economy (CE) has been emphasized by various sources (EASAC, 2016; Pauliuk, 2018; Saidani et al., 2019), leading to increasing research on CE indicators (Elia et al., 2017; Corona et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019). At research level, CE evaluation is commonly performed with environmentally assessment tools such as life cycle assessment (LCA) (Peña et al., 2021), material flow analysis (Barkhausen et al., 2023) and multi-criteria decision tools. (Allesch and Brunner, 2014; Campitelli and Schebek, 2020). However, these evaluations are based on comprehensive data which are often lacking (Zurbrügg et al., 2014) and requires additional research effort to generated the data required. As the result, in practice the evaluation of WM transition towards CE is performed with environmental indicators, predominantly the “recycling rate”, and more recently through benchmarking method (Fatimah et al., 2020; Whiteman et al., 2021; Campitelli et al., 2023)

Review of current WM performance evaluation practices reveals a significant gap in quantifying WM performance under the CE transition. Among the indicators used, "recycling rate", which has been used since the early WM era, emerges as the predominant WM

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performance indicator. (Ghisellini et al., 2016, Kirchherr et al. 2017, Moraga, 2019; Kristensen and Mosgaard, 2020, Morseletto, 2020, Luis, 2020; OECD, 2021; Panchal et al. 2021, Jerome et al., 2022), despite studies indicating its inadequacy in measuring CE (Di Maio, 2015; Haupt et al., 2017). This indicator lacks the ability to assess the linkage between CE and sustainability (Antunes et al., 2022), waste management efficiency (Iacovidou et al., 2017), the complexities of multiple cycles and the consequences of down cycling (Corona et al., 2019).

As a result, several WM related assessment matrices have been developed (Saidani et al., 2019), including the circular economy index (CEI) (Di Maio and Rem, 2015) for measuring circularity of a product, using longevity as measure of resource utilization (Franklin-Johnson et al. 2016), the material circularity indicator (MCI) for assessing the "degree of circularity" in product materials (EMF, 2015), the waste hierarchy index (WHI) for evaluating the WM compliance to the waste hierarchy concept (Pires, 2019). However, "recycling rate" remains as the dominant industrial waste performance indicator.

In view of the issues and challenges in evaluation WM performance under CE transition, this research is formulated based on the following research questions (RQ)

RQ1: What is the CE transition for waste management?

RQ2: What is the current state of WM performance evaluation?

RQ3: What is missing and how to address the issues?

This research introduces concept of "Circularity Performance" concept as the principle for evaluating industrial waste management performance. Building upon this concept, a novel indicator "recycling circularity" and developed two index systems: the "circularity performance index" (CPI) and the "dynamic circularity performance index" (DCPI), tailored for specific applications

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The CPI aims to address the existing gaps in general WM performance evaluation, including the absence of sustainability assessment framework, limited WM statistics available for conducting integrated assessment, and challenges in cross-sectoral application at different levels (micro, meso and macro). The CPI's novelty lies in the quantitative measurement of relative resource recovery efficiencies across various waste treatment processes from environmental, social, and economic perspectives. Utilizing general industrial waste management statistics, the CPI enables swift and holistic evaluation of circularity performance in WM systems and allows inter-sectoral comparison.

The CE serves as a guiding principle and requires customized implementation strategies tailored to the distinctive characteristics of the target industry This requires the identification of development trend through long-term evaluations. Ironically, none of the existing performance evaluation frameworks are designed to assess industry-specific WM performance over a defined period, and evaluation results obtained are insufficient for formulating industry-specific CE strategy. As a response to this gap, the Dynamic Circularity Performance Index (DCPI) has been developed to provide the necessary information through evaluation of long-term waste management data.

This study demonstrates the practical application of the circularity performance concept through the two case studies of (1) CPI assessment of 27 manufacturing sectors in 2021; and (2) DCPI assessment of the medical industry from 2014 to 2021.

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1.4 Research Framework

The structure of this paper is as shown in Figure 1. Chapter 2, the literature review offers comprehensive background information essential for the study. Chapter 3 will describe the research process and methods employed in the study. Chapter 4 will present the assessment results and key findings. Reflective remarks based on the findings will be discussed in chapter 5. are discussed in section base on the findings. The conclusions and some reflective remarks are drawn in chapter 6.

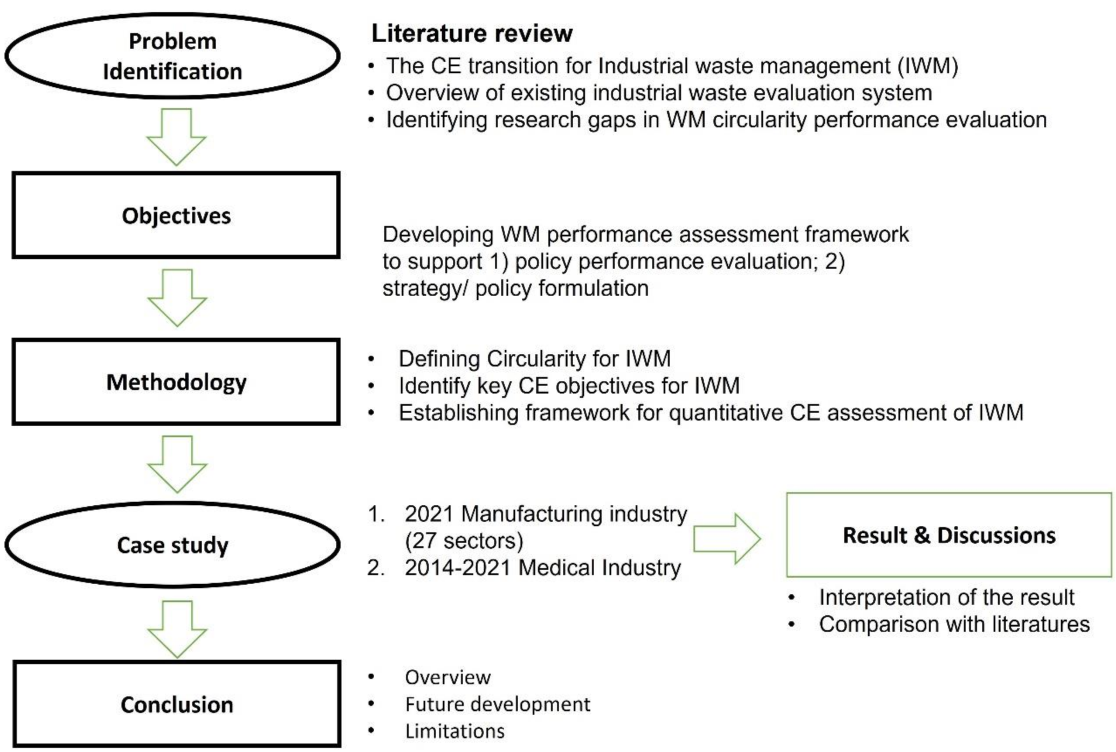

Figure 1. Research Framework

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Chapter 2 Literature Review

To understand the requirements for a practical industrial waste performance evaluation framework, this research conducted literature reviews in the three key areas of: (1) circular economy transition of industrial waste management; (2) current state of industrial waste management performance evaluation; and (3) overview of circularity evaluation tools and methods. By exploring these domains, the study sought to identify the key characteristics of WM to be evaluated, the limitation of existing waste management practice and the current research gaps to establish the foundation for formulating the circularity performance concept.

2.1 Sustainable development, circular economy and waste management

The terms "sustainable development" (SD)," "circular economy" (CE) and "industrial waste management" (IWM) are interrelated concepts with the common objectives of mitigating the negative impact of human activities to the environment. From management perspective, "sustainable development", which is defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (Bruntland, 1987), is the ideal condition to be realised and can be regarded as the ultimate vision. Circular Economy is the economic concept of which the strategies for achieving sustainability are based upon. Last but not least, industrial waste management is subdomain of environmental management particularity focusing on prevent degradation of environmental quality caused by inadequate management of industrial waste, and is undergoing transition towards a circular economy.

2.1.1 Sustainable development and circular economy

Numerous studies have attempted to establish the relationship between the sustainable development and circular economy. Li (2012) defined the CE as an economic model that

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seeks to achieve sustainable development by emphasizing environmental protection and pollution prevention. This concept was further expanded upon by Corona et al. (2019), who described circularity as the integration of environmental, economic, and social sustainability. The CE gained recognition as an environmentally friendly and restorative economic system that aims to reduce negative impacts from all sources (Rocha, 2020; Franco et al. 2021) emphasized the role of circularity in supporting organizations in making strategic decisions related to sustainability, considering the governance perspective.

Despite the absence of a universally accepted definition for the circular economy, many researches have been conducted to review the various CE definitions used (Kirchherr et al., 2017) concluded that the achieving sustainable development as the common goal.

2.1.2 Waste management and circular economy

The concept of waste appears in various definitions of the CE. For example, in a review of 70 CE definitions (Saidani et al., 2020), “waste” emerged as the sixth most frequently cited term. The focus on “waste hierarchy” within the CE aims to minimize waste and create a sustainable and zero-waste environment (Ranjbari et al., 2021). The design and management of efficient WM systems serve as a foundation for establishing the CE, enabling better resource management and waste prevention. (Zeller et al., 2019; Di Foggia and Beccarello, 2021)

In recent years, there has been a significant increase in research focused on WM practices aligned with the goals of the CE. These researches encompass a wide range of topics, including the development of CE indicators for WM (Luttenberger, 2020), the identification of WM drivers towards a CE (Calderón Márquez and Rutkowski, 2020), the exploration of barriers and challenges in transitioning to a CE (Zhang et al., 2019), the establishment of a waste hierarchy index for the CE (Pires and Martinho, 2019), and the examination of enablers

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for e-waste management in a CE (Sharma et al., 2020). In addition, various research teams have conducted quantitative analyses to gain comprehensive understanding of WM within the broader context of the CE. These studies focus on specific waste streams, including municipal solid waste management (Tsai et al., 2020), construction and demolition waste (Wu et al., 2019), plastic waste (Khan et al., 2019, Karayilan et al., 2021), and steel waste (Berlin et al., 2022).

However, the practical implementation of WM activities aligned with CE principles is still unclear in existing studies (Tsai et al., 2020), posing a challenge for WM policymakers and CE practitioners. As a result, there is a lack of a comprehensive map depicting WM research themes and trends from a CE perspective (Kristensen and Mosgaard, 2020).

In addition to the direct implications of CE for WM, there are numerous CE-related studies that indirectly impact WM. New business models are seen as drivers for maximizing value creation while minimizing resource consumption (Schulte, 2013, Bocken et al., 2016; Lieder and Rashid, 2016), and systematic analyses of various CE business models have been conducted (Chen et al., 2020; Pieroni et al., 2021). For example, adopting of the product leasing model incentivizes producers to implement circular design strategies, which are beneficial for WM. Additionally, consumers with greater environmental consciousness are willing to pay a circular premium for circular products, encouraging manufacturers to consider social and environmental attributes in their innovative products, such as green circular premiums and sustainability certifications (Appolloni, 2022). Research on the integration of CE and digital technologies with the potential to improve productivity and sustainability performance has also increased (Khan et al., 2021). Examples of such technologies include blockchain for digital material passports, RFID chips for waste monitoring, and artificial intelligence and neural networks for accelerated waste sorting

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(EEA, 2023).

Studies on the concept of circular economy rebound, which suggests that the perceived benefits of CE strategies may be lower than the potential benefits due to systemic changes including increased productivity and consumption, have indicated that this effect could result in waste generation and increased material use (Castro, 2022).

2.2 Current state of Industrial WM monitoring

Industrial waste management practices are commonly monitored and evaluated using environmental metrices. Reviews on current circular economy indicators consistently highlight the prominence of the "recycling rate" as the main performance indicator for waste management (Ghisellini et al., 2016; Kirchherr et al., 2017; Moraga, 2019; Kristensen and Mosgaard, 2020; Morseletto 2020; Luis, 2021; OECD, 2021, Panchal et al., 2021; Jerome et al. 2022)

The European Commission's Circular Economy Monitoring Framework (EU Eurostat, 2022) assesses waste management performance using "recycling rate" and "recycling/recovery rate of specific waste streams." Review of CE indicators by Calzolari et al. (2021) identified "waste landfilled", "recycled waste", "recovered waste" and "recyclability & ease of disassembly" as the most commonly employed assessment metrices for waste management.

On the other hand. studies have shown the limitations of using “recycling rate” as CE performance indicator. Material Flow Analysis study on Swiss waste management system (Haupt et., al, 2016) concluded that “recycling rate” is not a suitable CE performance indicator, as the indicator alone is insufficient in assessing overall quality, efficiency, and sustainability of WM (Iacovidou et al. 2017). This segmented indicator needs to be

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complemented by other indicators that capture different aspects of waste management to obtain a clearer understanding of waste hierarchy implementation. Furthermore, literature has described the application of “recycling rate” as CE indicator as "inaccurate", "misleading," and “contributing to wrong decision-making and limited innovation in the industry” (Di Maio, 2015). A comprehensive review of CE indicators (Antunes et al., 2022). concluded that new indicators are needed as current ones do not address the link between CE and sustainability. The CE requires robust and continuous product cycles, such as upcycling rather than downcycling (Dieterle et al., 2018), which are not adequately captured by the recycling rate.

“Recycling rate” is defined as the “proportion of waste generated that is recycled" and was a suitable indicator for the transition from sound disposal towards a recycling-based society. The indicator is limited in addressing the CE transition due to the way due to its inherent nature. “Recycling rate” specifically refers to amount of waste entering recycling stream and not the resource recovery efficiency which is the core of the CE implementation. Unlike the “waste hierarchy” which prioritizes treatment processes according to the relative sustainability of the waste treatment operations, “recycling rate” does not distinguish between treatments and hence the “recycling rate” for waste incinerated for energy recovery, which is regarded as the least sustainable according to the waste hierarchy, is the same as recycling as raw materials. In other words, “recycling rate” as performance indicator only shows the quantity of waste recycled and not the overall recycling quality.

2.3 Overview of circularity evaluation tools and methods

The CE is gaining increasing prominence in research and indicators are needed to assess the implementation practices and guide decisions to achieve the model (Pires and

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Martinho, 2019). Literature review (Sassanelli et al., 2019) shows that conventional environmental assessment methods including life cycle assessment (LCA), material flow analysis (MFA), environmentally extended input-output analysis (EEIOA), multi criteria decision methods (MCDM), data envelopment analysis (DEA), design for x (DfX), emergy and exergy approach (Em/Ex), and discrete event simulation (DES) have all been applied for assessing circular economy.

LCA is the most frequently used method for quantification of the environmental impact throughout the entire life cycle of a product, as it aligns with the current focus of researchers on the environmental dimension of CE (Merli et al., 2018) and covers most of its aspects, including the use of natural resources, the use of renewable and recyclable resources, and reductions in emissions and valuable material losses (Haupt et al., 2019). Variations of LCA including Life cycle costing (LCC) and social life cycle assessment (S-LCA) have been developed to evaluate the economic and social impacts of a product's life cycle (Fauzi et al., 2019). LCA has been applied to industrial waste related research, such as LCA based eco-efficiency assessment framework in the textile dying industry (Angelis-Dimakis et al., 2016), assessment of treatment and valorisation of waste (Laso et al., 2018), LCA based assessment tools of waste in urban context (Hadzic et al., 2018) and assessment of the used materials and by-products in biofuels (Martin et al., 2017).

Material Flow Analysis (MFA) is commonly used to systematically assess the flow and stock of materials within a certain spatio-temporal boundary (Brunner and Rechberger, 2004; Wang and Ma, 2018; Westin et al., 2019) for it provides comprehensive quantitative inventory of material flow at national, regional and corporate levels (Ma, 2021). Economy-Wide MFA has been applied to assess urban metabolism by quantifying "Direct Material Input" and "Domestic Material Consumption" (Voskamp et al, 2017).

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CE indicators can be seen as managerial and policy-making instruments to create goals, perform analysis or communicate externally about significant issues (Saidani et al., 2019). As the CE has different definitions (Kirchherr et., al 2017, Parchomenko et al., 2019), an in-depth understanding of the CE concept is required in developing CE indicator (Blomsma and Brennan, 2017). As CE operates on macro, meso and micro levels (Pauliuk 2018), the tools and indicators for measuring CE differs depending on the level of application (Su et al., 2013). Currently. there is a considerable number of indicators and it can be challenging to find the most suitable one for evaluation (Saidani et al., 2019). However, indicators for measuring CE are still at an early level of development (Giurco et al., 2014, Mesa et al., 2018).

CE metrics utilize established evaluation methods. LCA has been employed to complement the material circularity indicator (MCI) and broaden the scope of CE assessment by identifying potential environmental trade-offs not captured by the MCI (Lonca et al., 2018). Furthermore, MFA is utilized to establish general circularity metrics like the cyclical use rate (measuring recycling) and the proportions of secondary materials in the inputs and outputs of the system (Tanzer and Rechberger, 2019), categorized by resource type such as energy, biomass, or metals and minerals (Mayer et al., 2019). The EU's CE indicators pertaining to the material footprint of its members rely on MFA, while the category rules for the product environmental footprint and circular footprint formula are based on LCA (Zampori and Pant, 2019).

The above discussions on CE metrics shows the importance of applying and comparing diverse methods in CE assessment, as each method has unique applications. Numerous research studies have focused on developing environmental matrices for WM. Di Maio and Rem (2015) introduced the Circular Economy Index (CEI), which considers strategic, economic, and environmental aspects of recycling to provide decision-making support with

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concise information. Franklin-Johnson et al. (2016) developed a performance indicator based on longevity, which measures the duration of resource utilization. The Ellen MacArthur Foundation (EMF, 2015) proposed the Material Circularity Indicator (MCI) to assess the "degree of circularity" in product materials. The "Waste Hierarchy Index (WHI)" (Pires and Martinho, 2019) evaluates the level of waste hierarchy implementation by considering various forms of recycling and incineration and assigning weights based on their contribution to the CE. Despite the tremendous research efforts, there is currently no widely acknowledged, universally agreed-upon, or standardized index for WM systems that is applicable across countries or industrial sectors (Zaman, 2015).

2.4 Challenges in measuring circularity of industrial waste management

The literature review above provides a clear overview of the issues and challenges in the current industrial waste management performance assessment. There is a lack of standardized methods for quantitative evaluation the sustainability aspects of a CE due to its multidisciplinary nature. Similarly, in the context of WM, there is a lack of clarity regarding the practical implementation of CE principles, posing challenges for policymakers and CE practitioners in the selection of suitable performance indicator. Moreover, the dominant use of "recycling rate" as WM performance indicator falls short in capturing sustainability benefits. While some alternative environmental matrices have been developed to assess CE, only a few are specifically tailored for WM, such as the Ternary Diagram and the Waste Hierarchy Index. However, these methods remain primarily research tools and have not been widely adopted by authorities for assessing WM. The establishment of a well-defined performance matrics would enhance communication with stakeholders and establish a connection to the sustainable development goals outlined by the United Nations. Table 1

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shows the list of issues with current CE indicators that are addressed as criteria for the new indicator in this research.

Table 1. **Identified issues and challenges with current CE indicators for waste management**

	Issues	References
1	No commonly recognized or standardized index system for waste management performance that is applicable across countries and industrial sectors.	*Zaman*, 2015
2	Indicators for measuring CE are still at an early stage of development	*Giurco* et al., 2014*; Mesa* et al., 2018
3	Assessing waste management using end of life resource efficiency indicators including recycling rate of specific waste stream and no dedicated indicator for industrial waste	*Moraga* 2019, *Luis* 2021, *OECD* 2021
4	Insufficient existing data to support conventional environmental assessment such as	*Zurbrügg* et al., 2014
5	Limitation of current practice using "recycling rate" as the main indicator for waste management, including	
5.1	- misleading and inaccurate contributed to wrong decision making and poor innovation	*Di Maio* 2017
5.2	- "recycling rate" alone is not capable of measuring the overall waste management quality, efficiency, and sustainability.	*Iacovidou* et al. 2017
5.3	- failure to address the linkage between circular economy and sustainability	*Corona* et al.,2019, Antunes et al., 2022
5.4	- insufficient to address the complexities of multiple cycles and consequences of material up/down cycling	*Corona* et al.,2019

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Chapter 3 Methodology

Based on the issues and challenges in WM performance assessment shown in Table 1, this research formulated the essential characteristics of an ideal WM performance indicator. This led to the subsequent establishment of the "circularity performance" concept for waste management to delineate the sustainability of waste management practices.

Two index systems were derived from this concept. The "circularity performance index" (CPI) is a general policy performance assessment index to enable quantitative and integrated sustainability evaluation of WM practice while allowing inter-sectoral comparison using standard WM data. On the other hand, the "dynamic circularity performance index" (DCPI) is tailored to support industry-specific strategy and policy formulation. DCPI assesses performance over a specific timeframe, offering industry-specific insights into the trends and obstacles faced during the transition towards a circular economy.

The "circularity performance evaluation framework" has been established to facilitate the standardized execution of performance assessment. This evaluation framework consists of four stages, including (1) scoping; (2) data collection and preparation; (3) calculation; and (4) evaluation.

3.1 The "Circularity Performance" concept for waste management

The "circularity performance" concept was developed for assessing the sustainability of current waste management practices. It serves as a solution to the prevailing challenges and issues encountered in the evaluation of WM performance shown in Table 1. The concept is formulated based on the visions for an ideal WM performance assessment method, including: (1) specific to industrial waste management; (2) utilization of existing waste management statistics without the need for additional research; (3) integration of

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environmental, economic and social considerations inherent in the circular economy; (4) addressing CE features such as up/down cycling and multiple cycle; (5) allowing inter-industrial comparison; (6) facilitating industry-specific assessment; (7) enabling time-series performance analysis to assess developmental trends.

The waste management system development stage concept (WMS-DSC) describes the transition of WM towards CE by shifting the goal from "expansion the recycling industry" to "waste as a resource" (Campitelli et al., 2023). Similarly, the WM circular performance concept 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 quantity to include the additional dimension of optimizing the efficiency of the resource recovery process. Figure 2 illustrates the circularity performance concept as the evolution of waste management performance assessment, transitioning from a purely quantitative perspective to an integrated approach considering both quantity and quality aspects.

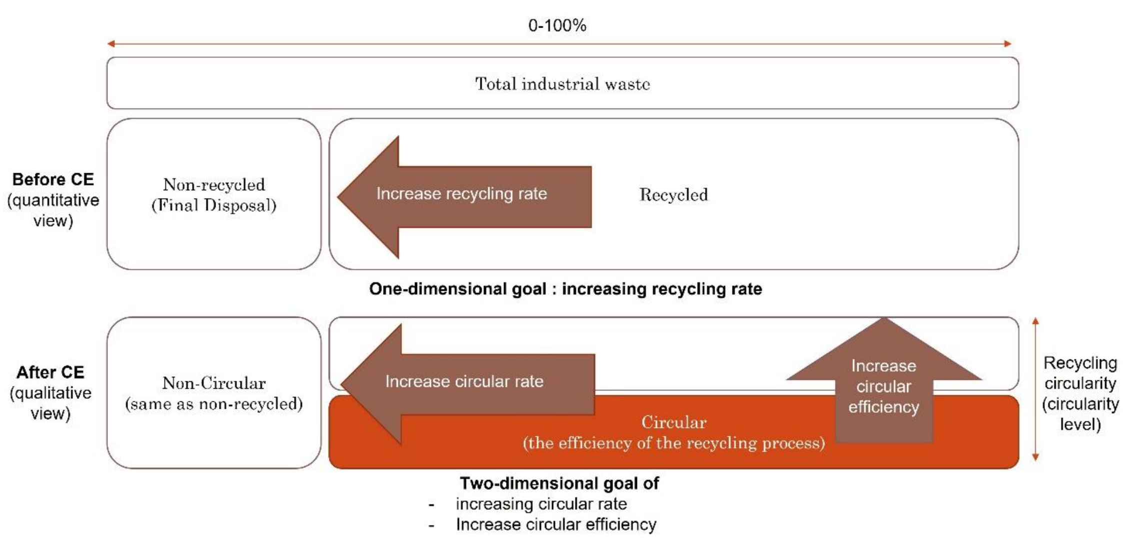

Figure 2. The circularity performance concept

In a conventional recycling-based system, industrial wastes are divided into recycled and non-recycled, with the one-dimensional sustainability preference of increasing the

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recycling rate. The system considers only the quantity of waste that enters the recycling streams and disregards the quality of the recycling processes. The shift towards a circular economy calls for additional economic and social benefits through the maximization of resource intensity. Hence in the circularity performance concept, industrial wastes are categorised as circular and non-circular with two-dimensional sustainability preferences of increasing the circular rate (horizontal axis) and increasing circular efficiency (vertical axis). Hence, the general circularity performance equation is defined as

Circularity performance = Circular rate * Circular efficiency

3.1.1 The Circularity Performance Index (CPI)

The circularity performance index (CPI) refers to the quantified circularity performance obtained through quantification of both the "circular rate" and "circular efficiency".

The term "circular rate" refers to the amount of waste entering the waste recycling stream and is equivalent to the definition of the "recycling rate". Therefore, in the CPI equation, "circular rate" is substituted with commonly used indicator "recycling rate".

Conversely, the notion of "circular efficiency" measures the effectiveness of individual recycling processes and does not align with any pre-existing indicator. To solve this gap, a new indicator named "recycling circularity" is introduced to represent the "circular efficiency'. This new indicator quantitatively measures the relative recycling efficiency from environmental, economic and social perspectives. Thus, the full equation for the Circularity Performance Index (CPI) is formulated as follows:

Circularity Performance Index (C_P) = Recycling rate (R) * Recycling circularity (Rc)

The definitions for the key terms are as follows, and the equations are presented in Table 5.

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Circularity performance index (C_P): the overall circularity efficiency for industrial waste management from a sustainability perspective, calculated as the product of the recycling rate and recycling circularity.

Recycling rate (R): 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.

Recycling circularity (Rc): the relative efficiency level of the waste recycling process, calculated by dividing the cumulative circularity level by the maximum circularity level of the waste generated.

The "circularity level" concept is introduced to allow quantification of "recycling circularity". Detail of the concept is illustrated in section .3.1.2.

3.1.2 The "circularity level" approach for quantification of recycling circularity

The "circularity level" refers to the classification of "recycling circularity" with respect to the relative sustainability preference and is introduced to enable quantification of recycling circularity. It is established through the procedure of :(1) defining key CE criteria for waste management and the sustainability preferences: (2) establish classification of circularity; (3) establish procedure for quantifying recycling circularity.

3.1.2.1 Identification of circular economy criteria and sustainability preferences

Circular economy is a general term with different definitions depending on the application. For waste management, the European Commission adopted a "waste hierarchy" which ranks waste management options from most to least preferred in the order of "prevention", "minimization", "reuse", "recycling", "energy recovery" and "disposal" (EC, 2008). The Chinese Circular Economy Promotion Law (China, 2008) defined CE as "the reduce, reuse and recycle activities conducted during production, circulation and

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consumption". The Ellen MacArthur Foundation advocates CE value creation through "the inner circle", "circling longer", "cascaded use" and "pure input" for (EMF et al., 2014). The McKinsey Center introduced the ReSOLVE framework of "Regenerate", "Share", "Optimise", "Loop", "Virtualize" and "Exchange" as actions for circular transition (McKinsey, 2016). Kirchherr et al. (2017) reviewed 114 definitions of CE and concluded that the most common elements are "reduce", "reuse", "recycle", "system perspective" and "economic perspective".

The identified key CE factors and respective sustainability preferences are shown in Table 2.

Table 2. Review of key elements of circular economy

Key Circular economy reference	Key Factors	Source
Waste Hierarchy	Prevention, minimisation, reuse, recycling, energy recovery, disposal, in order of from most to least favourable with reference to sustainability	European Commission (2008)
Circular Economy Promotion Law of the People's Republic of China	Reducing, reusing and recycling activities conducted during the production process, circulation and consumption	Standing Committee of the National People's Congress (2008)
Four principles for value creation	The power of - The inner circle - Circling longer - Cascaded use - Pure input	Ellen MacArthur Foundation (2012)
ReSolve Framework	Regenerate, Share, Optimize, Loop, Virtualize, Exchange	McKinsey and Company (2016)
Review of 114 circular economy definitions	Reduce, Reuse, Recycle, System Perspective, Economic Perspective	Julian Kirchherr, et al. (2017)

The above CE definitions were recategorized into environmental, economic and social perspectives, and the following key elements were identified.

(1) Environmental: the ecological efficiency of the treatment process used. From the perspective of natural resource circulation, the ranking from most to least favourable

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is “return to the original resource”, “transform into material”, “transform into energy” and “return to biosphere”.

(2) Economic: the economic value of the resource from both absolute and relative perspectives. The absolute economic value refers to the market demand and is assessed based on whether the waste generated has a positive or negative market value. A positive value indicates that the waste producer received money for providing the waste for treatment, and a negative value indicates that the waste producer needs to pay for the waste to be treated. The relative value refers to the economic value after the treatment process. CE encourages the “upcycling” of waste for higher economic value and discourages “downcycling” due to its relatively low market value.

(3) Social: optimizing resource intensity by keeping the resource within society for as long as possible, measured by the number of loops enabled within the recycling process.

The identified key CE factors and respective sustainability preferences are shown in Table 3.

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Table 3. Key CE factors and sustainability preferences

Sustainability aspect	CE factor	Sustainability preference	Definition
Environmental (waste hierarchy)	Return to the original resource	Preference in descending CE factor column order	The waste resource is returned to the original form
	Recycle as material used for new products		The waste resource is used as material for new products
	Recycle as an energy source		This waste resource is used as an energy source
	Return to the biosphere		The waste resource is reused through its return to the biosphere
Economic (value)	Absolute value (+/−)	Preference for a positive absolute value over a negative absolute value	A positive absolute economic value indicates that the waste is sold and shows market demand A negative absolute economic value indicates that the waste generator pays for the waste to be treated and there is less market demand
	Relative value	Preference for higher economic value	The value of the derived product that undergoes the same treatment process
Social (loops)	Number of loops	Preference for a higher number of loops	The higher the number of loops, the higher the resource intensity

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3.1.2.2 Circularity classification for industrial waste management

The key CE factors for environmental, economic and social perspectives were integrated with the respective sustainability preference to establish the classification of circularity as shown in Table 4. A total of nine distinct circularity classes were established, each representing a division of recycling circularity based on the identified sustainability criteria. Class 1 is the most favourable division in terms of sustainability, while class 9 is the least favourable.

For example, Class 1 is defined as "unlimited recycling as raw material in the original form". This recycling approach aligns with the preference set in the "waste hierarchy" which is the guiding principle from environmental perspective. "Raw material" denotes a resource with the highest possible value, reflecting a preferred choice from the economic standpoint. "Unlimited recycling" indicates the maximum number of cycles through which the resource can be part of a product providing functionality service to fulfil societal needs. In contrast, Class 2 exhibits relatively lower sustainability when compared to Class 1 due to the fewer potential loops. Conversely, Class 9 is defined as "direct return to the biosphere without treatment and a negative market value", exemplifying recycling methods such as direct reclamation, which do not undergo treatment processes with the waste generator bearing the associated cost.

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Table 4. Classification of circularity

Environmental (hierarchy)				Economic (value)		Social (loop)		Circularity class	Definitions
Returned to the original material	Derived product	Energy source	Returned to the biosphere	Absolute value (+/ -)*	Value of the derived product	No. of loops	Re-entering the loop		
X				positive	same	unlimited	Yes	1	Unlimited recycling as raw material in the original form
X				positive	decrease	multiple	Yes	2	Multiple recycling as raw material in the original form
X				positive	decrease	multiple	Yes	3	Multiple recycling as raw material in different forms
	X			positive	higher	single	Yes	4	Single recycling as an additive with a higher market value (upcycling) and the potential for further recycling
	X			positive	lower	single	Yes	5	Single recycling as an additive with a lower market value (downcycling) and the potential for further recycling
	X			positive	lower	single	No	6	Single recycling as an additive with a lower market value (downcycling) and no potential for further recycling
		X		negative	decrease	single	No	7	Single recycling as an energy source with no potential to be reused and a negative market value
			X	negative	decrease	single	No	8	Single recycling returned to the biosphere with no potential to be reused and a negative market value
			X	negative	-	single	No	9	Direct return to the biosphere without treatment and a negative market value

* positive absolute value indicates that the waste generator sells the waste generated for recycling
** negative absolute value indicates that the waste generator needs to pay for the waste to be recycled
*** relative value of the derived product (upcycling/downcycling)
**** number of loops

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3.1.2.3 Quantification procedure for “recycling circularity”

The “circularity level” denotes the weighting attributed to a circularity class from a perspective of relative sustainability. Circularity class characterized by higher environmental preference, economic value and social benefits will receive correspondingly higher circularity level. For example, recycling for resource recovery as raw material has a higher circularity level than recycling for energy recovery.

The first step in quantifying “recycling circularity” involves determining the number of “circularity level” to be employed for the specific study. It is accomplished by pairing the inventory of waste recycling processes with the classification of circularity presented in Table 4 and assigning circularity level based on their respective sustainability preferences.

Using the waste management data from Taiwan’s environmental Protection Administration (TEPA) as example. The list of recycling processes is as shown in Appendix A-1. By pairing this list with the circularity class, it is found that seven distinctive circularity levels can be identified, using the available waste management data. Consequently, a circularity level of 7 is adopted with level 7 to 1 assigned in a descending order of sustainability preference, where level 7 represents the most sustainably favourable and level 1 the least favourable. The result is as shown in Table 5.

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Table 5. Example of circularity level determination

Treatment code	Circularity class	Definition	Circularity level
G01, R01	C1	Unlimited recycling as raw material in original form	CL7
R02	C2	Multiple recycling as raw material in original form	CL6
	C3	Multiple recycling as raw materials in different forms	
	C4	Multiple recycling as raw materials in different forms with a higher market value (upcycling)	
R03	C5	Single recycling as additives of other products	CL5
R04	C6	Single recycling as an energy source with no potential to be reused and a negative market value	CL4
R05, R06	C7	Single recycling returned to the biosphere with no potential to be reused and a negative market value	CL3
R07,	C8	Direct return to the biosphere without treatment and a negative market value	CL2
R08, R09, R10, R99	C9	Single recycling as an energy source with no potential to be reused and a negative market value	CL1

With the established circularity level for the study, the computation of "recycling circularity (R_C)" can be performed by calculating the "circularity level score (C_{Ln})", "cumulative circularity level score (C_T) according to the respective equation outlines in Table 6.

Circularity Level score (C_{Ln}): refers to the product of the assigned circularity level and the weight of the recycled waste in the specific circularity level, where n is the circularity level assigned to the respective recycling process.

Cumulative circularity level score (C_T): refers to the summation of all circularity level scores for all circularity levels assigned.

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3.1.3 The Dynamic Circularity Performance Index (DCPI) Concept

Figure 3 shows the graphical illustration of the evolvement from CPI to DCPI.

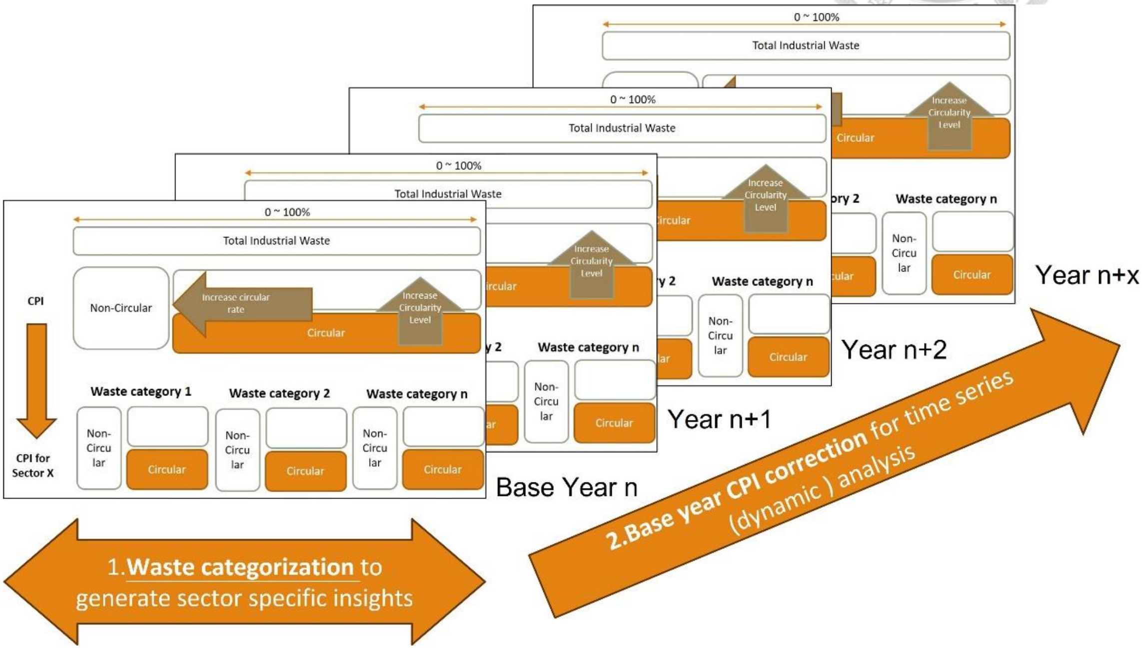

Figure 3. Schematic illustration of the dynamic circularity performance index (DCPI) concept

Dynamic Circularity performance Index (DC$_P$) = Circularity Performance (C$_P$) * Base Year Correction Factor (C$_F$)

Base-year correction factor refers to the ratio of waste generation in the assessment year to the base year.

Strategy formulation and policy assessment requires insights on the development trend over time with references to the distinctive characteristics of the target industry. Currently there is no index system designed to assess the performance of a specific industry over a period of time. While original CPI offers a static measure of performance at the specific point in time, allowing cross-industry comparisons within the same

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assessment year, it has been observed that directly comparing CPI results across different assessment year can result to misinterpretation, particularly when there are significant fluctuations in total waste generation. The DCPI is introduced as a modification of the original CPI by incorporating two new processes of (1) waste characterization; and (2) base-year CPI correction” as solution to the issues mentioned above.

“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.

“Base-year CPI correction” is introduced to enable comparison of the chronological CPI performances to convert CPI to DCPI through “base-year correction factor”. A base-year is selected as a reference benchmark and the “base-year correction factor” is calculated as the ratio of total waste generation of the assessment year to the base-year. This conversion from CPI to DCPI allows comparison of different assessment years. Full definitions and equations for calculating CPI and DCPI are as shown in Table 6.

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Table 6. Definitions and equations of parameters

No.	Term	Unit	Definitions and equations
1	Total waste generated (W_{TG})	Tonnes	Refers to the amount of waste generated by a particular manufacturing sector under circularity level n. $W_{TG} = W_1 + W_2 + W_3 + \ldots + Wn$ n ranges from 1 to the number of circularity levels used.
2	Total recycled waste (W_{TR})	Tonnes	Refers to the waste resources generated by the manufacturing sector that are recycled. Total recycled waste (W_{TR}) is the sum of all recycled waste under circularity level n. $W_{TR} = W_{R1} + W_{R2} + W_{R3} + \ldots + W_{Rn}$ n ranges from 1 to the number of circularity levels used.
3	Recycling rate (R)	Percentage	The recycling rate is the proportion of recycled waste among total waste generated. $R = W_{TR}/W_{TG} * 100\%$
4	Circularity level score	Unitless	Refers to the product of the assigned circularity level and the weight of the recycled waste. $C_{Ln} = n * W_{Rn}$ n is the assigned circularity level of the recycling process.
5	Cumulative circularity level score (C_T)	Unitless	Refers to the sum of all circularity level scores for all circularity levels assigned. $C_T = C_{L1} + C_{L2} + C_{L3} + \ldots + C_{Ln}$

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No.	Term	Unit	Definitions and equations
6	Recycling circularity (R_C)	Unitless	Refers to the average circularity score as an indicator of relative circularity efficiency with respect to the target of concern (sector, city, waste type, etc.). This parameter is calculated by dividing the cumulative circularity level score by the total weight of the waste generated. $R_C = C_T / W_{TG}$
7	Circularity performance (C_P)	Unitless	Refers to the overall circularity of all industrial waste generated. It is the product of the recycling rate and recycling circularity. $C_P = R \times R_C$
8	Base Year Correction Factor (C_F)	Unitless	Refers to the ratio of waste generation in the assessment year to the base year. It is calculated by dividing the total waste generation in year n + x by the total waste generation in year n, where year n is the base year and x is the no. of years after year n. $C_F^{n+x} = W_{TR}^{n+x} / W_{TR}^{n}$
9	Dynamic Circularity performance (DC_P)	Unitless	Refers to the base year corrected circularity performance converting the circularity performance from nominal to real number. It is the product of C_P^{n+x} and $C_F^{n+x,}$ where year n is the base year and x is the no. of years after year n. $DC_P^{n+x} = C_P^{n+x} * C_F^{n+x,}$

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3.2 Circularity Performance Evaluation Framework

3.2.1 Framework structure

The schematic representation of the circularity performance evaluation framework is as shown in Figure 4. The evaluation framework consists of four stages: (1) scoping; (2) data collection and compilation; (3) calculation; and (4) evaluation. The first two stages are the pre-calculation preparation phase, which remains the same disregard the research objective and the waste management data quality. The calculation stage has two separate procedures. The static analysis is for general policy performance evaluation of current status. “Static” refers to non-industry specific analysis using a single year’s data and it allows comparison across different industries. The dynamic analysis is to support policy analysis and formulation, which requires industry-specific insights and understanding of the development trend over time. In the evaluation stage, 3 different forms of analysis, namely index interpretation, quadrant analysis and circularity level distribution are introduced to allow better understanding of the calculation results.

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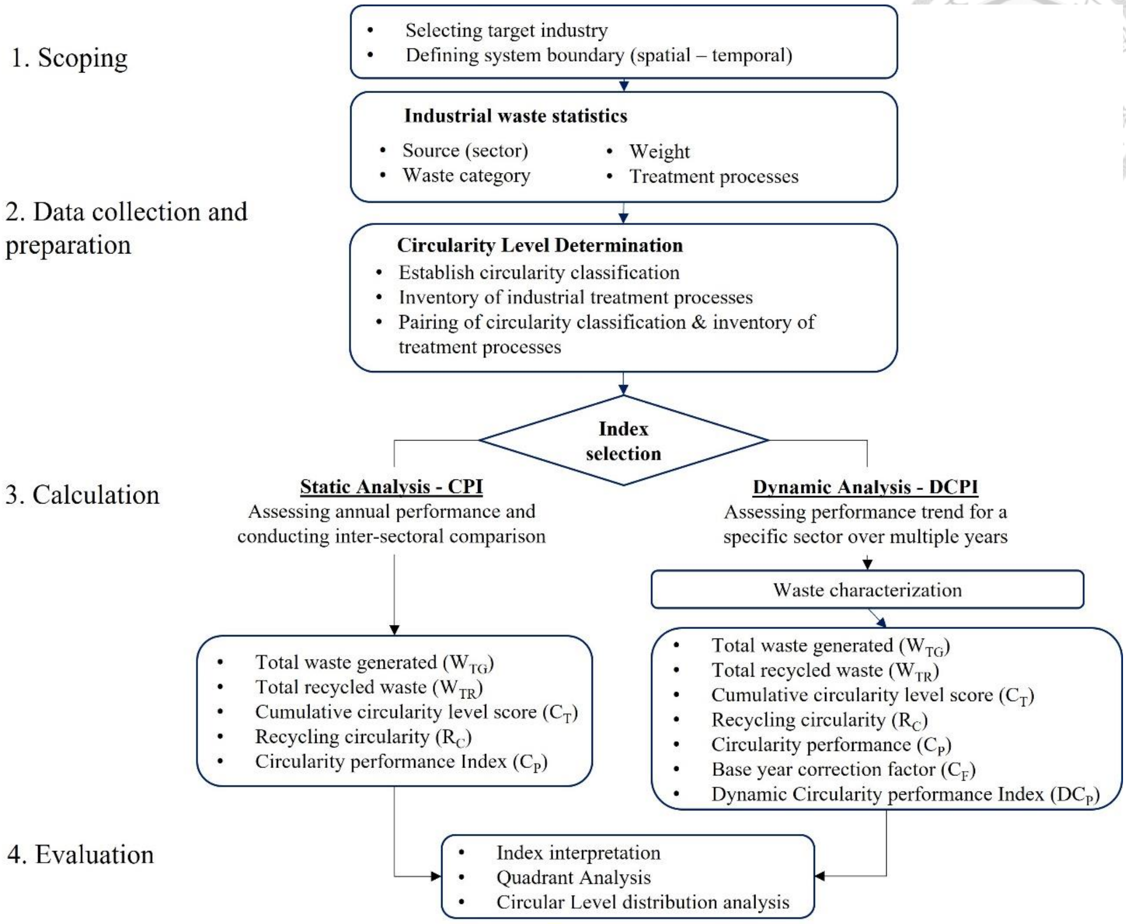

Figure 4. The circularity performance evaluation framework

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

3.2.2 Scoping

The scoping stage serves to define the spatial, temporal and industrial boundaries of the system under consideration. The spatial boundary can be set at the national, regional or city level. Regarding the temporal boundary, the CPI is for evaluating data from a single year, while the DCPI is more appropriate for assessing development trend using multiple-year data. As for the industrial boundary, this assessment can be applied at both industry level and the sectoral level, depending on the specific focus of the

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analysis and the comprehensiveness of the waste management data used.

3.2.3 Data collection and preparation

In the "data collection and preparation" stage, the required waste statistics are collected. The minimum information required for calculating CPI includes (1) waste generation source (industry or sector); (2) waste generation quantity; (3) waste type; and (4) waste treatment methods.

3.2.4 Calculation

The calculation stage involves several preparatory tasks, such as "waste characterization", to identify the major waste categories, and "circularity level determination" achieved by pairing the recycling process inventory with the classification of circularity (Table 4). Subsequently, calculation of indicators including "recycling rate", "recycling circularity", "CPI" and "DCPI" can be performed using the collected industrial waste statistics.

3.2.4.1 Circularity level determination

The "circularity level" approach is adopted to enable quantification of "recycling circularity" from the relative sustainability preferences of the waste recycling processes. Detail procedure and example using TEPA's waste management data are as illustrated in section 3.1.2.3.

3.2.4.2 Waste Characterization

"Waste characterization" refer to the systematic classification of the generated

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waste by the distinctive characteristics of 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.

3.2.4.3 Calculation procedure

Calculation of CPI and DCPI require general waste management statistical data including: (1) waste generation source (industry or sector); (2) waste generation quantity; (3) waste type; and (4) waste treatment methods. With these the various variables calculation can be performed. Full definitions and equations of the indicators are as shown in Table 6.

3.3 Result interpretation

To facilitate interpretation of the calculated result, this study introduces the 3 methods of (1) result ranking; (2) quadrant analysis; and (3) circularity level distribution. The description of the three methods are as follows.

3.3.1 Result ranking

The is important to recognize that the numerical output of "recycling circularity" is derived from the relative circularity level rather than the absolute circularity efficiency. To facilitate ease of interpretation and comparison, it is advisable to employ relative ranking instead of the exact numerical value. However, it is crucial to bear in mind that these rankings are solely intended for illustrative purpose and does not affect the actual

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result. An example of the ranking comparison is shown in Table 7.

Table 7. Example of CPI result ranking comparison

Sector Name	Recycling rate (R)	R ranking	Recycling circularity (R_C)	R_C ranking	Circularity performance Index (C_P)	C_P ranking
Sector A	95.96%	2	0.58	2	0.56	1
Sector B	97.85%	1	0.52	3	0.51	2
Sector C	40.16%	3	0.8863	1	0.36	3

In the example above, sector A ranks 2nd in both "recycling rate" and "recycling circularity", achieving 1st in overall "circularity performance index".

3.3.2 Quadrant Analysis Diagram

The quadrant analysis diagram is design to allow a simple and clear visual display of the overall circularity performance, with the horizontal (x) axis as the "recycling rate and the vertical (y) axis as "recycling circularity". Example of the quadrant analysis diagram is as shown in Figure 5 below.

Figure 5. Example of quadrant analysis diagram

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The quadrant analysis diagram consists of 4 areas. Top right quadrant is referred to as the “high performing”, indicating above 50% performance in both recycling rate and recycling circularity. The bottom right quadrant is the “quantity centric” quadrant, indicating a better performance in “recycling rate” over “recycling circularity”. The top left quadrant is referred to as the “efficiency centric” quadrant, indicating a better performance in “recycling circularity” over “recycling circularity”. The bottom quadrant is the “low performing” quadrant, with poor performance in both “recycling rate” and “recycling circularity”.

3.3.3 Circularity level distribution

The circularity level distribution is designed to provide a clear visual illustration of “recycling circularity” through the percentage of waste recycled under each circularity level. Example of the circular distribution chart is as shown in Figure 6. In this example, the waste recycling activity in sector C is concentrated at higher circularity level (CL) 7 (20%) and CL6 (20%) whereas majority of the waste recycled in Sector A and B are CL 5 or below.

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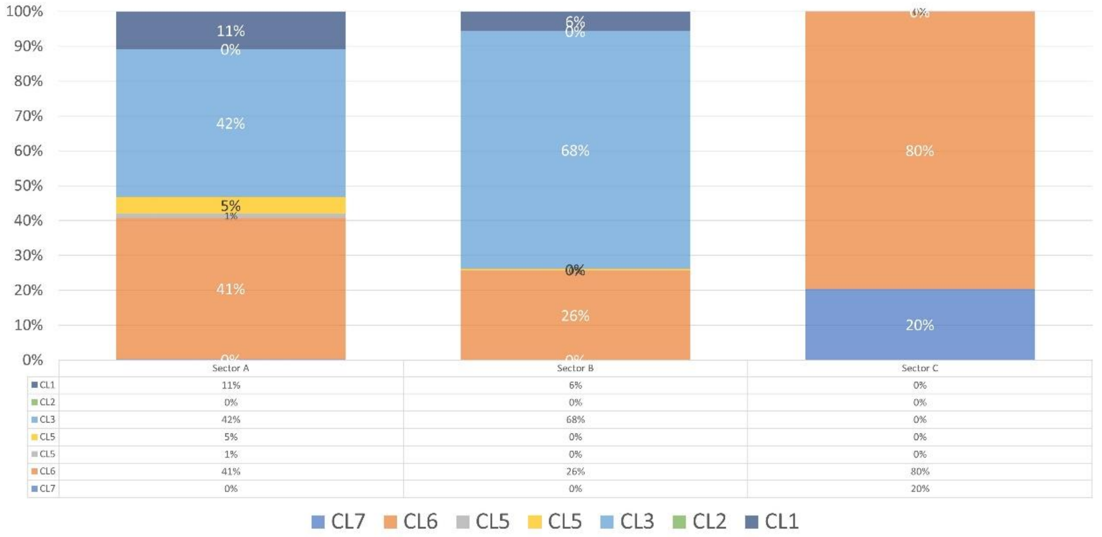

Figure 6. Example of circularity distribution chart (colour coded)

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Chapter 4 Results

Two case studies were performed to verify the application of circularity performance concept.

Case study 1 is the evaluation of 194 manufacturing sub-sectors (4-digit sector code) based on the 2021 industry waste generation data by TEPA. This resembles a typical annual industry performance evaluation and is CPI is used for the assessment. For convenience, the result is represented as 27 sectors (2-digit sector code).

Case 2 is the evaluation of medical industry CE transition based on the industrial waste generation data from 2014-2021. This resembles a typical assessment to support formulation of industry strategy, which is often industry-specific with assessment over a period of time. For this reason, DCPI is used for the case study

4.1 Case Study 1: CPI - 2021 Taiwan Manufacturing Industry (27 sectors)

4.1.1 Background

Industrial waste is one of the major waste categories and concern for sustainability. Effective waste management (WM), reduction while meeting market demand are the keys in achieving a sustainable and zero-waste society (Ranjbari et al., 2021). In 2011, global industrial waste generation (including construction waste) was approximately 9.2 billion tonnes, equivalent to about 1.74 tonnes per capita per year (Vignesh et al., 2021). In 2018, industrial waste accounted for 10.6% of the total waste generated in the EU, with varying

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percentages per country, ranging from 1% to 46.6% (Eurostat, 2021). Industrial waste management is of particular importance especially for manufacturing-based economy such as Taiwan. In 2021, Taiwan generated 21.95 million tonnes of industrial waste, of which 19.13 million tonnes (87.17%) originated from the manufacturing sector (TEPA, 2021).

4.1.2 Scoping

The scope of this case study was the assessment of the industrial waste generated by manufacturing sectors in year 2021.

4.1.2.1 System boundary

The system boundary is set within the "waste management" stage as defined by European Union's Circular Economy Monitoring Framework, which is from the generation of waste to the treatment of waste. The EU CE monitoring framework categorised the entire life cycle of a resource into the 4 stages of: (1) production and consumption, (2) waste management, (3) secondary raw material and (4) competitiveness and innovation. This study examines how waste resources are treated to allow further resource circulation that takes place at the "waste management" stage. Waste minimization, which is also an important aspect of a circular economy, is taking place during the "production and consumption" stage and hence not included within the scope of this research.

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4.1.2.2 Industry classification

This study follows the 11th revision of the "Statistical Classification of Industries", the latest industry classification from the Taiwanese Directorate General of Budget, Accounting & Statistics released in January 2021. The classification was established based on the United Nation's "International Standard Industrial Classification for all economic activities" (ISIC) and is revised every five years with survey data from the annual Industry, Commerce and Service Census.

The statistical classification of industries consists of four tiers. The tabulation categories, identified by letters, are called "sections"; the 2-digit categories, "divisions"; the 3-digit categories, "groups" and the 4-digit categories, "classes".

The manufacturing sector is under Section C of the statistical classification of industries from division 08 to 34 and is further divided into 84 groups and 194 classes. Calculations for this research were performed at class level (194 classes), and for convenience, the results shown are aggregated at the division level. The full list of manufacturing sectors in 2-digit sector division code is as shown in the Table 8.

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Table 8. 2-digit sector division code used in the case study

Sector Code (2 digit)	Sector Name
08	Manufacture of Food Products and Prepared Animal Feeds
09	Manufacture of Beverages
10	Manufacture of Tobacco Products
11	Manufacture of Textiles
12	Manufacture of Wearing Apparel and Clothing Accessories
13	Manufacture of Leather, Fur and Related Products
14	Manufacture of Wood and of Products of Wood and Bamboo
15	Manufacture of Paper and Paper Products
16	Printing and Reproduction of Recorded Media
17	Manufacture of Petroleum and Coal Products
18	Manufacture of Chemical Material and Fertilizers
19	Manufacture of Other Chemical Products
20	Manufacture of Pharmaceuticals and Medicinal Chemical Products
21	Manufacture of Rubber Products
22	Manufacture of Plastic Products
23	Manufacture of Other Non-metallic Mineral Products
24	Classified Manufacture of Basic Metals
25	Manufacture of Fabricated Metal Products
26	Classified Manufacture of Electronic Parts and Components
27	Classified Manufacture of Computers and Electronic and Optical Products
28	Manufacture of Electrical Equipment
29	Manufacture of Machinery and Equipment
30	Manufacture of Motor Vehicles and Parts
31	Manufacture of Other Transport Equipment and Parts
32	Classified Manufacture of Furniture
33	Other Manufacturing
34	Repair and Installation of Industrial Machinery and Equipment

4.1.2.3 Industrial waste recycling processes

The waste treatment data used contains a list of 20 recycling processes as shown in Appendix A-1. This inventory of treatment processes is later paired with the classification of circularity to establish of the circularity level used by the study.

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4.1.3 Data Collection and preparation

This study follows the 11th revision of the "Statistical Classification of Industries", the latest industry classification from the Taiwanese Directorate General of Budget, Accounting & Statistics released in January 2021. The classification was established based on the United Nation's "International Standard Industrial Classification for all economic activities" (ISIC) and is revised every five years with survey data from the annual "Industry, Commerce and Service Census".

The statistical classification of industries consists of four tiers. The tabulation categories, identified by letters, are called "sections"; the 2-digit categories, "divisions"; the 3-digit categories, "groups" and the 4-digit categories, "classes". The manufacturing sector is under Section C of the statistical classification of industries from division 08 to 34 and is further divided into 84 groups and 194 classes. Calculations for this research were performed at class level (194 classes), and for convenience, the results shown are aggregated at the division level. The full list of manufacturing sectors in 2-digit sector division code is as shown in the table below.

The 2021 data consisted of approximately 369,000 waste generation entries from 183 4-digit sector classes with 297 waste types and 40 different treatment processes. The result is aggregated to 27 2-digit sector divisions (division 08 to 34) according to the latest "Statistical classification of industries" (DGBAS 2021). For example, sector "08" refers

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to the sector of "manufacture of food products and prepared animal feeds" and sector "09" refers to "manufacture of beverages".

The research determined the circularity levels to be used for evaluation by pairing the "classification of circularity" with the inventory of waste recycling processes. The 20 recycling processes in the waste statistics were matched to seven out of nine circularity classes, and the result is shown in Table 5. Additional information on the recycling cost and the state of the material when it is being recycled was needed to further pair the recycling processes to the two remaining circularity classes

4.1.4 Calculation

Calculation of "recycling rate", "recycling circularity" and "circularity performance index" is performed according to the definition and equation set in Table 6.

4.1.5 Results

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

4.1.5.1 Numerical result and ranking of the calculated result

Table 9 shows the numerical calculation results and the respective ranking for "recycling rate", "circularity performance" and "recycling circularity". It is important to note that the circular level concept refers to the relative sustainability of the recycling processes and the numerical result of "recycling circularity" does not represent the

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absolute but relative recycling efficiency of the sector. The interpretation of the result is performed using rankings instead of the numerical result to avoid confusion and to provide a simple illustration of the overall performance. For example, sector “09” ranks 1 out of 27 in terms of “recycling rate”. However, the sector ranks 23 out of 27 in terms of “recycling circularity” and as a result, it ranks 11 out of 27 in overall “circularity performance index”.

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Table 9. Recycling rate, circularity performance and recycling circularity results.

Sector code	Recycling rate (R)	R ranking	Recycling circularity (R_C)	R_C ranking	Circularity performance (C_P)	C_P ranking
08	95.96%	3	0.58	21	0.56	8
09	97.85%	1	0.52	23	0.51	11
10	65.78%	16	0.59	20	0.39	16
11	87.60%	6	0.75	12	0.65	5
12	0.00%	27	0.00	27	0.00	27
13	51.57%	20	0.85	5	0.44	14
14	73.97%	12	0.66	18	0.49	13
15	72.20%	13	0.72	14	0.52	10
16	27.69%	26	0.92	2	0.25	24
17	74.61%	11	0.85	4	0.64	6
18	81.58%	10	0.44	25	0.36	17
19	85.27%	8	0.36	26	0.31	21
20	44.45%	21	0.48	24	0.21	26
21	88.78%	5	0.92	1	0.82	1
22	66.07%	15	0.59	19	0.39	15
23	97.61%	2	0.84	6	0.82	2
24	91.79%	4	0.77	10	0.71	3
25	62.61%	18	0.53	22	0.33	20
26	63.87%	17	0.82	7	0.53	9
27	33.29%	25	0.71	16	0.24	25
28	34.31%	24	0.77	11	0.27	23
29	51.83%	19	0.67	17	0.35	19
30	66.59%	14	0.73	13	0.49	12
31	36.23%	23	0.78	9	0.28	22
32	82.83%	9	0.8026	8	0.66	4
33	86.67%	7	0.7106	15	0.62	7
34	40.16%	22	0.8863	3	0.36	18

4.1.5.2 Quadrant analysis

Figure 7 presents the quadrant analysis diagram, which has been designed to visually compare the circularity performance of different manufacturing sectors. The diagram is divided into four quadrants, each representing a different performance

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category.

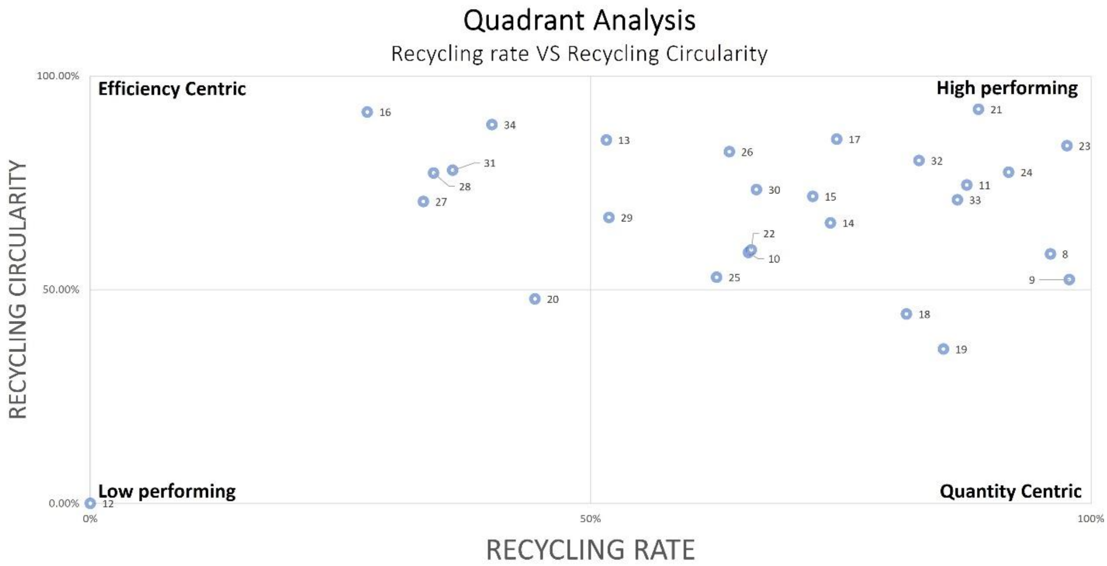

Figure 7. Quadrant analysis diagram

The top right quadrant is referred to as the "high performing" quadrant, indicating sectors that exhibit both parameters (recycling rate and recycling circularity) above the sector mean.

The top left quadrant represents the "efficiency centric" quadrant, where sectors demonstrate above-average recycling efficiency but fall behind in terms of recycling rate.

The bottom right quadrant is the "quantity centric" quadrant, showing sectors with an above-average recycling rate but below-average efficiency.

The bottom left quadrant displays sectors with below-average performance in both recycling rate and recycling circularity.

In addition to their relative position on the diagram, the number of sectors in each quadrant provides an overview of performance distribution. In this case, there are 17

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sectors in the high performing quadrant, 2 sectors in the quantity centric quadrant, 5 sectors in the efficiency centric quadrant, and 2 sectors in the last quadrant.

4.1.5.3 Circularity level distribution diagram

Figure 8 shows the circularity distribution of the 27 sectors to provide a simple overview of the “recycling circularity” of each sector. The percentage shown in the bar is the percentage of waste recycled through the circularity level shown in Table 5. Take sector “09” as example, the diagram shows a distribution of 6% in CL1, 68% in CL3 and 26% in CL6. The concentration of waste treated with low CL processes resulted in the relative low ranking in recycling circularity.

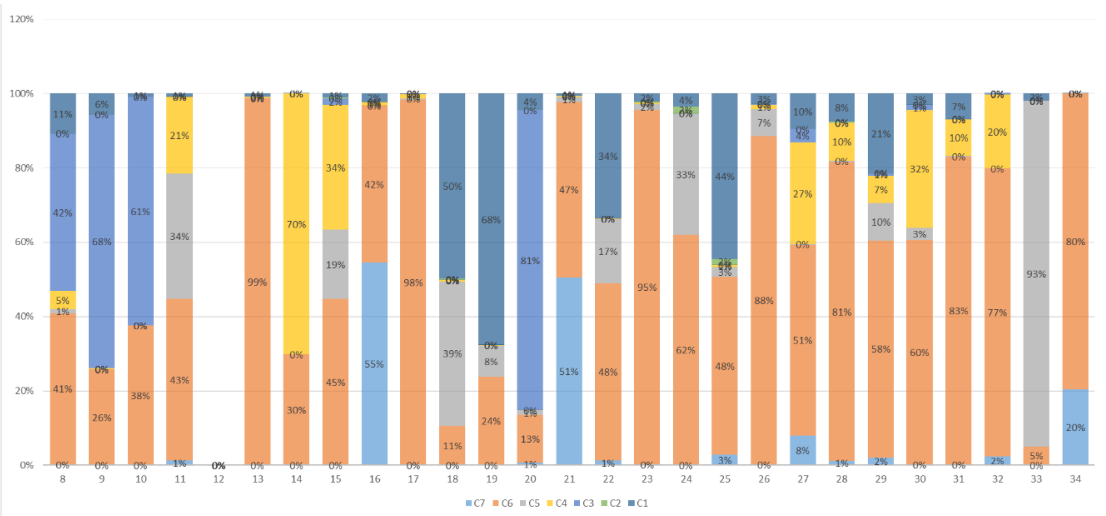

Figure 8. 2021 Taiwanese industrial waste circularity level distribution. X-axis: sector codes. Circularity levels are colour-coded.

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4.1.6 Key findings

(1) A high recycling quantity is not equivalent to a high recycling efficiency

Sectors with high and low recycling rates were examined to verify correlation with recycling circularity. The results show only a weak correlation between the two, suggesting that the recycling rate alone is insufficient as a CE indicator for waste management.

(a) The beverage manufacturing sector (sector 09)

This sector had the highest recycling rate of 97.85% but ranked 23 out of 27 in recycling efficiency. As a result, it ranked 11 out of 27 in circularity performance index. Figure 8 shows the concentration of waste recycling in low circularity level processes, as 68% of the wastes were recycled as feedstock or fertilizer (CL3) while only 26% were recycled as raw material (CL 6 & 7).

(b) The manufacturing sector for food products and prepared animal feeds (sector 08)

With the 3rd highest recycling rate of 95.96%, this sector ranked 21 out of 27 in recycling circularity, and as a result, 8th in overall circularity performance index. Figure 8 shows that 53% of wastes were treated with circularity level 3 and below.

(c) The manufacturing sector of other non-metallic mineral products (sector 23)

This sector performed well with a 97.61% recycling rate (2nd) and recycling

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circularity (6th). As a result, it ranked 2nd in circularity performance index.

The lower end of the recycling rate ranking also provides interesting insights. Sectors 16, 27 and 28 were the three sectors with the lowest recycling rates (27.69%, 33.29% and 34.31%, respectively) and may be regarded as low circularity sectors if the recycling rate is used as the indicator. The recycling circularity ranking of these three sectors was 2nd, 16th and 11th, respectively, which shows that sectors with a low recycling rate do not necessarily perform poorly in terms of recycling efficiency.

The observed inconsistency in the recycling rate and recycling efficiency ranking suggests a weak correlation between the two. Pearson's correlation coefficient between recycling rate and recycling circularity was 0.2047, which indicates a weak or negligible correlation.

(2) Recycling circularity as an indicator of available treatment options

Among the 27 sectors evaluated, recycling circularity score ranged from 0 to 92.21%, with an average of 67.62%, indicating large variations among sectors.

The top two sectors in recycling circularity were the manufacturing of "rubber products" (sector 21) and "printing and reproduction of recorded media" (sector 16), with scores of 92.91% and 91.6%, respectively. In terms of recycling rate, these two sectors rank 5th and 26th, respectively, exhibiting a weak correlation between the two parameters. The lower end of the recycling circularity spectrum shows a similar result. The sectors

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for both the "manufacturing of "chemical products" (sector 19) and "chemical materials and fertilizers" (sector 18) had low recycling circularity scores of 36.14% and 44.3%, respectively, but above-average recycling rates, ranking 8th and 10th.

The recycling rate can constitute a significant indicator of waste management effort during the transition from sound final disposal to a recycling-based society, but not for the transition from recycling to a circular economy. An evaluation based on recycling rate neglects the fundamental difference in the type of waste generated by individual sectors. For waste generators, recycling decisions are based on legal requirements, costs and technological availability. The lack of available cost-effective recycling technology options can result in a low recycling rate. Recycling circularity provides an indication of the recycling capacity and options for waste generated by different sectors, which is of particular importance to public authorities.

(3) High circularity performance requires both quantity and quality of recycling

Achieving high circularity requires a balance between the quantity and quality of recycling. The results show that the top five sectors in circularity were among the top 10 in terms of recycling rate and recycling circularity. For example, the "rubber product manufacturing sector" (sector 21) ranked 1st in circularity, 5th in the recycling rate (88.78%) and 1st in recycling circularity (92.21%). The manufacturing of "other non-metallic mineral products" (sector 23) ranked 2nd in the circularity chart, 2nd in recycling

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rate and 6th in recycling circularity. This shows that in comparison with using only recycling rate as a performance indicator, circularity performance index provides a better overview by incorporating both quantitative and qualitative aspects of industrial waste treatment.

The average CPI for the 27 sectors was 0.5631; the recycling rate and recycling circularity scores were 83% and 0.6785, respectively. This shows excellent performance in the quantity of waste recycled as well as room for further improvement in the quality of the recycling. The circularity class distribution chart shows that 21% of industrial waste was treated with processes that do not allow further recycling in the original form (circularity level 5 and below), and 16% of waste was recycled for use in land related recycling applications, such as landscaping, land use alterations or land reclamation.

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4.2 Case study 2: DCPI for 2014-2021 Taiwan medical industry

4.2.1 General background

In the past decade, the medical industry has experienced significant growth, leading to a substantial increase in the generation of medical waste (Kenny, 2021). 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. (WHO, 2014). The terms "medical waste" and "healthcare waste" are used interchangeably. (Yoon et al., 2022). 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, biomedical research centres and laboratories. (TEPA, 2020). The toxic, infectious and hazardous nature of medical waste has raised significant concerns regarding environmental impact, health implication, overall well-being (Chauhan et al., 2021) and requires more sustainable and safe management practices.

On one hand, despite its high recycling 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

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of medical waste (Ranjbari et al., 2021).

On the other hand, The CE transition for medical waste management has receive significant policy support. The European Environment and Health Process roadmap (WHO Regional Office for Europe, 2017) recognizes the CE transition as a guiding framework and highlighted the benefit of applying waste hierarchy to prevent adverse environmental and health effects, as well as addressing cost and inequality issues related to waste management. (WHO Regional Office for Europe, 2017; Ranjbari et al., 2021). However, despite this policy level backing and the potentially high recycling rates, the single-use mindset in the medical industry remains 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 wastes, despite evidence of its negative health and environmental impact (Ranjbari et al., 2021).

Extensive research has been conducted in the field of medical waste management over the past decade, focusing on topics such as appropriate treatment methods for safe disposal (Li et al., 2020; Chauhan et al., 2021; Singh et al., 2021), sustainability management of medical waste (Alharbi et al., 2021) and the development of indicators for medical waste management (Barbosa and Mol, 2018, Ferronato et al., 2020). 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 (Voudrias, 2018), smart

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industry 4.0 enabled medical waste disposal system (Chauhan et al., 2021), and developing CE indicator for the healthcare industry to adequately measure and monitor the progress of medical waste management strategies (Ranjbari et al., 2021).

4.2.2 Scoping

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 "waste management" stage as defined by European Union's circular economy monitoring framework. Detail information can be found in Appendix B

4.2.3 Data collection and preparation

For this study, waste generation data from hospitals and clinics in Taiwan between 2014 and 2021, amounting to a total of approximately 707 kilo-tonnes was used. The waste generated encompass 121 different types, and a variety of 26 treatment methods were employed. The inventory of recycling processes and the circularity level used is the same as case study 1, which is as shown in Table 8 and Table 9 respectively.

4.2.4 Calculation

4.2.4.1 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

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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 medical waste' and "recyclable medical waste", based on TEPA's waste codes. A complete definition of each category and the respective waste codes can be found in Table 10.

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Table 10. Classification of medical waste for case study 2

Waste Category	Definition	Taiwan EPA Waste Code
Hazardous medical waste (excluding biomedical waste)	Includes Manufactured hazardous industrial waste and scrap metal	Class B and C wastes (excluding C-05)
Biomedical waste	refers to waste produced in the course of medical treatment, medical testing, autopsies, quarantine inspections, research, or the manufacture of chemical agents or biological materials by medical treatment organizations, medical testing institutions, medical laboratories, industrial and research organization laboratories of biological safety grade two or above, or laboratories engaged in genetic or bio-technological research.	Class C-05
General medical waste	Waste produced by industry that is not hazardous industrial waste	Class D
Recyclable waste	Recyclable and reusable waste	Class R

4.2.4.2 Calculation

Calculation of "recycling rate", "recycling circularity", "CPI", "base-year correction factor" and "DCPI" is performed according to the definition and equation set in Table 6.

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4.2.5 Result

4.2.5.1 General results

Table 11 below shows the calculated results for "recycling rate", "recycling circularity", "CPI" and "DCPI" for all medical waste categories. It is important to note that the circular level concept pertains to the relative sustainability of the recycling processes, and the numerical values of "recycling circularity" represent relative recycling efficiency within the sector, rather than absolute values.

The Figure 9 to 13 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 key findings are explained in section 4.2.6

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Table 11. Full result on recycling rate, recycling circularity, circularity performance index and dynamic circularity performance index

		2014	2015	2016	2017	2018	2019	2020	2021	Average
Total Medical Waste	Recycling Rate	18.18%	9.50%	21.35%	29.14%	33.89%	33.12%	12.20%	21.90%	22.41%
	Recycling Circularity	61.94%	73.34%	72.44%	65.45%	64.86%	63.33%	65.76%	65.66%	66.60%
	Circularity Performance Index	11.26%	6.97%	15.47%	19.07%	21.98%	20.98%	8.02%	14.38%	14.77%
	Dynamic Circularity performance Index	11.26%	10.68%	10.28%	12.14%	15.88%	15.71%	25.64%	15.67%	16.75%
Biomedical Waste	Recycling Rate	12.52%	9.15%	21.77%	23.63%	29.31%	24.63%	8.63%	17.83%	18.43%
	Recycling Circularity	71.89%	72.82%	72.20%	72.38%	72.27%	71.95%	72.55%	71.65%	72.21%
	Circularity Performance Index	9.00%	6.66%	15.72%	17.11%	21.18%	17.72%	6.26%	12.77%	13.30%
	Dynamic Circularity performance Index	9.00%	12.67%	11.70%	11.53%	16.22%	14.42%	27.26%	15.41%	14.78%
Hazardous Waste	Recycling Rate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Recycling Circularity	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Circularity Performance Index	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	Dynamic Circularity performance Index	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
General Waste	Recycling Rate	0.39%	0.06%	0.11%	0.23%	0.24%	0.22%	0.10%	0.07%	0.18%
	Recycling Circularity	17.44%	43.24%	40.67%	38.47%	42.46%	41.65%	42.24%	46.82%	39.12%
	Circularity Performance Index	0.07%	0.02%	0.04%	0.09%	0.10%	0.09%	0.04%	0.03%	0.06%
	Dynamic Circularity performance Index	0.07%	0.04%	0.04%	0.06%	0.07%	0.06%	0.04%	0.05%	0.05%
Recyclable Waste	Recycling Rate	50.58%	86.03%	83.13%	90.48%	91.95%	97.10%	96.69%	95.48%	86.43%
	Recycling Circularity	53.57%	75.59%	73.37%	56.05%	53.02%	53.13%	53.33%	56.51%	59.32%
	Circularity Performance Index	27.10%	65.03%	60.99%	50.72%	48.75%	51.59%	51.57%	53.95%	51.21%
	Dynamic Circularity performance Index	27.10%	11.27%	12.62%	22.82%	25.89%	31.31%	38.16%	27.67%	24.61%

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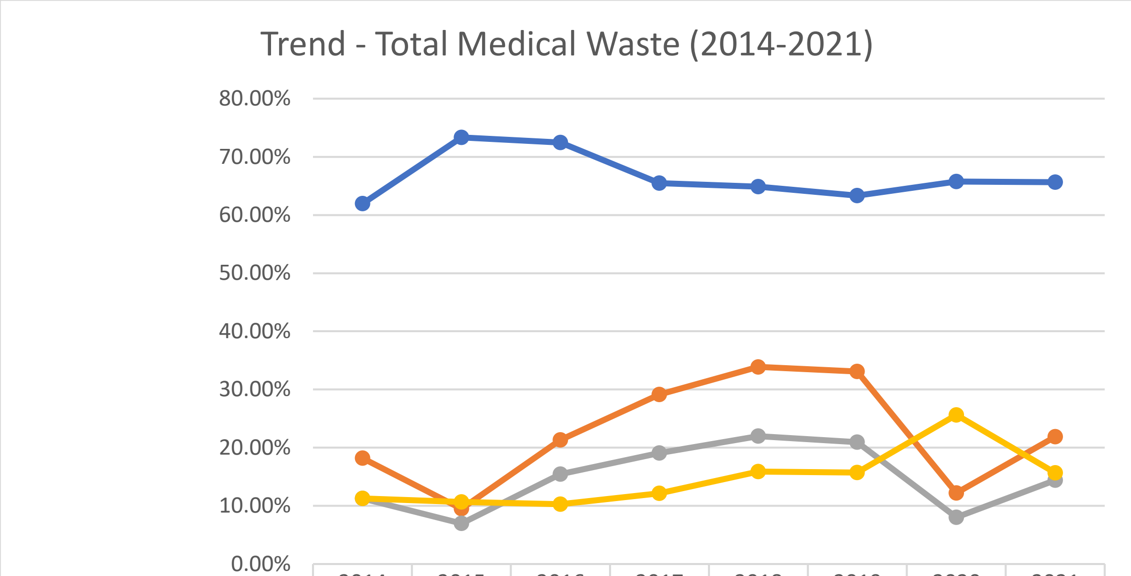
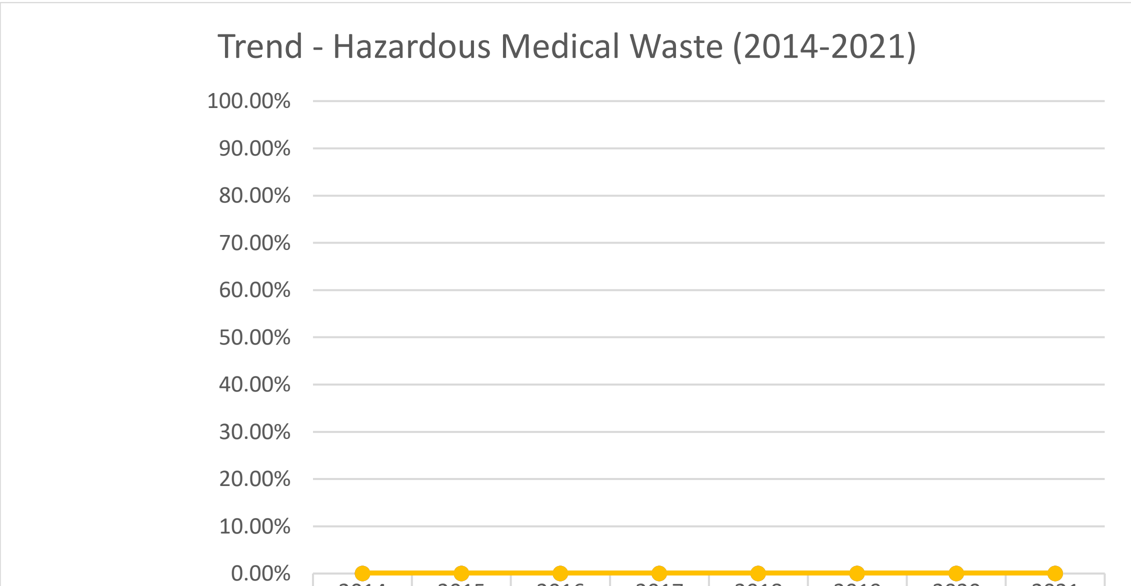


	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity	61.94%	73.34%	72.44%	65.45%	64.86%	63.33%	65.76%	65.66%
Recycling rate	18.18%	9.50%	21.35%	29.14%	33.89%	33.12%	12.20%	21.90%
CPI	11.26%	6.97%	15.47%	19.07%	21.98%	20.98%	8.02%	14.38%
DCPI	11.26%	10.68%	10.28%	12.14%	15.88%	15.71%	25.64%	15.67%

Figure 9. Calculation result for total medical waste



	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Recycling rate	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CPI	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
DCPI	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 10. Calculation result for hazardous medical waste

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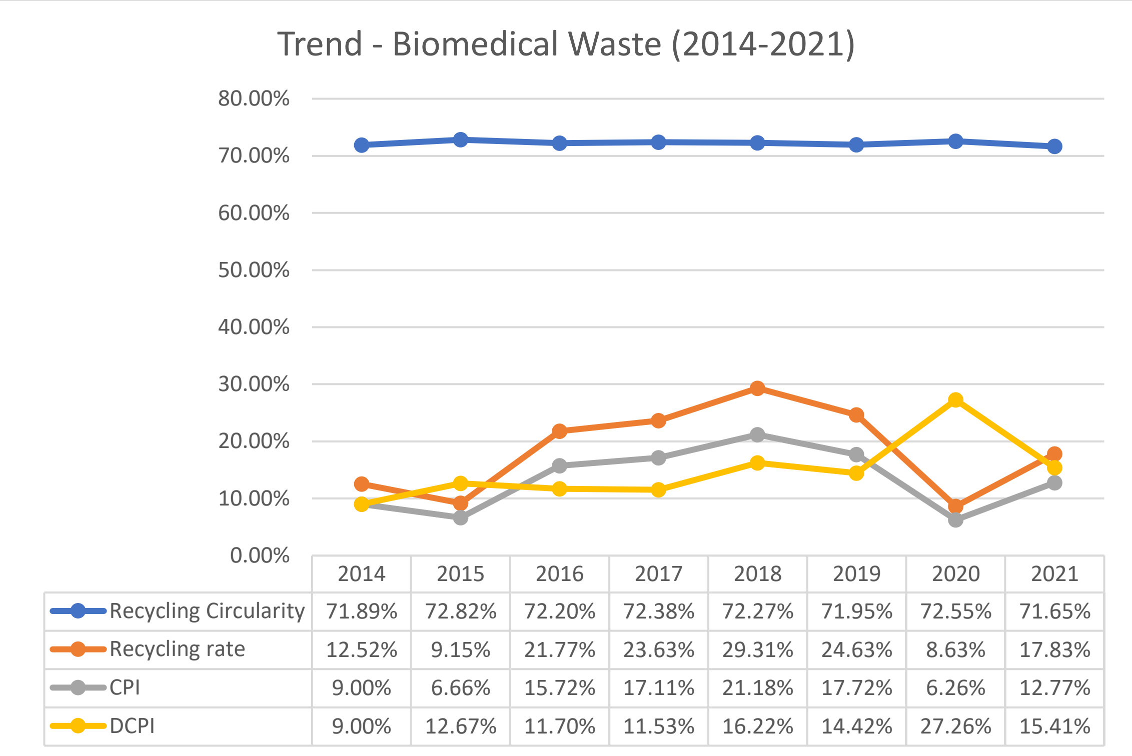
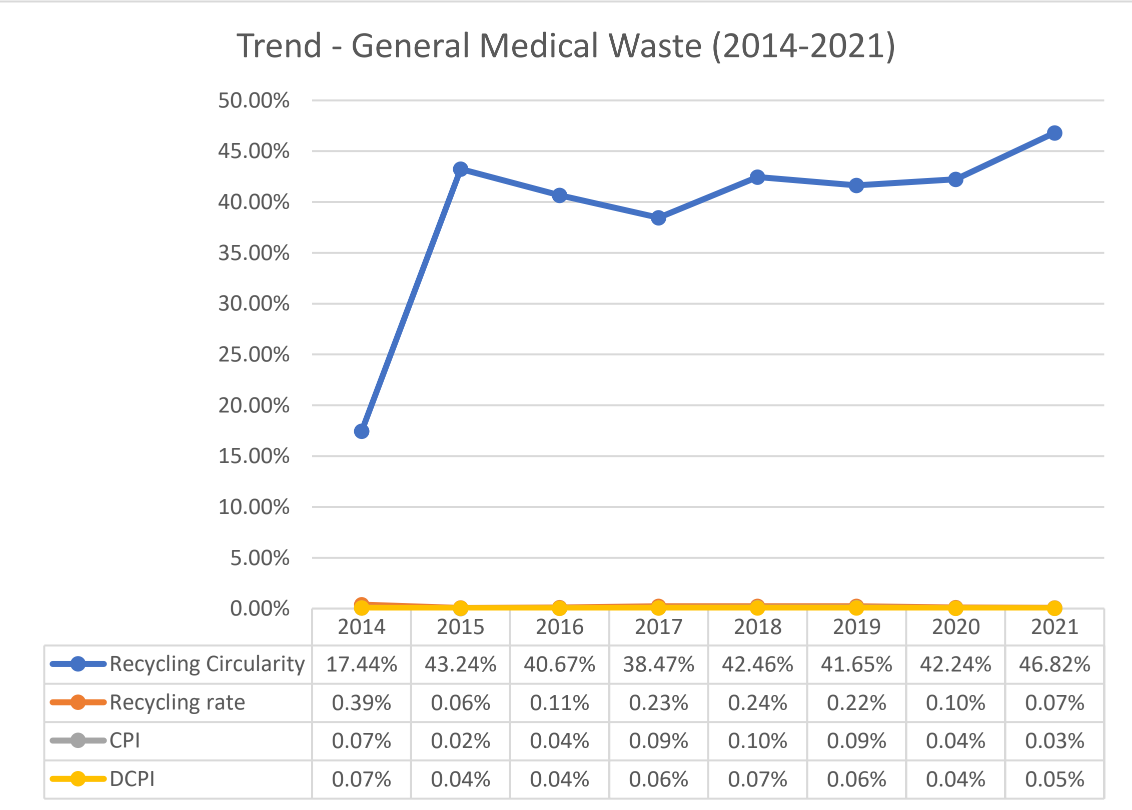


	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity	71.89%	72.82%	72.20%	72.38%	72.27%	71.95%	72.55%	71.65%
Recycling rate	12.52%	9.15%	21.77%	23.63%	29.31%	24.63%	8.63%	17.83%
CPI	9.00%	6.66%	15.72%	17.11%	21.18%	17.72%	6.26%	12.77%
DCPI	9.00%	12.67%	11.70%	11.53%	16.22%	14.42%	27.26%	15.41%

Figure 11. Calculation results for biomedical waste



	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity	17.44%	43.24%	40.67%	38.47%	42.46%	41.65%	42.24%	46.82%
Recycling rate	0.39%	0.06%	0.11%	0.23%	0.24%	0.22%	0.10%	0.07%
CPI	0.07%	0.02%	0.04%	0.09%	0.10%	0.09%	0.04%	0.03%
DCPI	0.07%	0.04%	0.04%	0.06%	0.07%	0.06%	0.04%	0.05%

Figure 12. Calculation results for general medical waste

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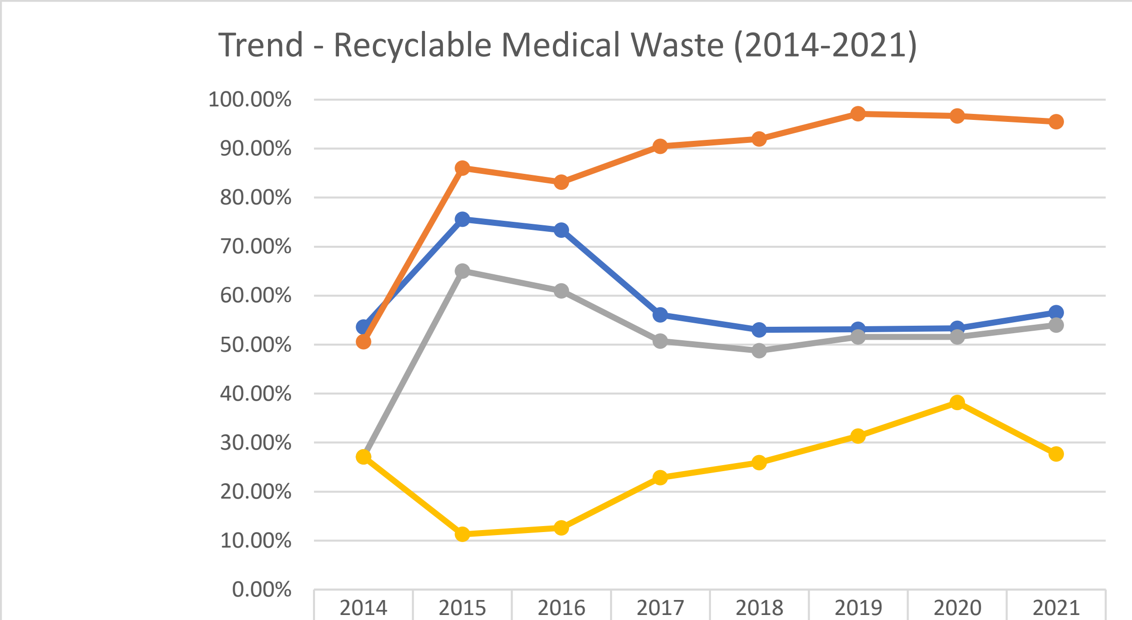

	2014	2015	2016	2017	2018	2019	2020	2021
Recycling Circularity	53.57%	75.59%	73.37%	56.05%	53.02%	53.13%	53.33%	56.51%
Recycling rate	50.58%	86.03%	83.13%	90.48%	91.95%	97.10%	96.69%	95.48%
CPI	27.10%	65.03%	60.99%	50.72%	48.75%	51.59%	51.57%	53.95%
DCPI	27.10%	11.27%	12.62%	22.82%	25.89%	31.31%	38.16%	27.67%

Figure 13. Calculation results for recyclable medical waste

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4.2.5.2 Quadrant analysis

Figure 14 to 18 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 (recycling rate) and quality (recycling circularity) 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 (recycling rate) and quality (recycling circularity).

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 (recycling circularity) compared to the quantity of recycling (recycling rate).

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

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

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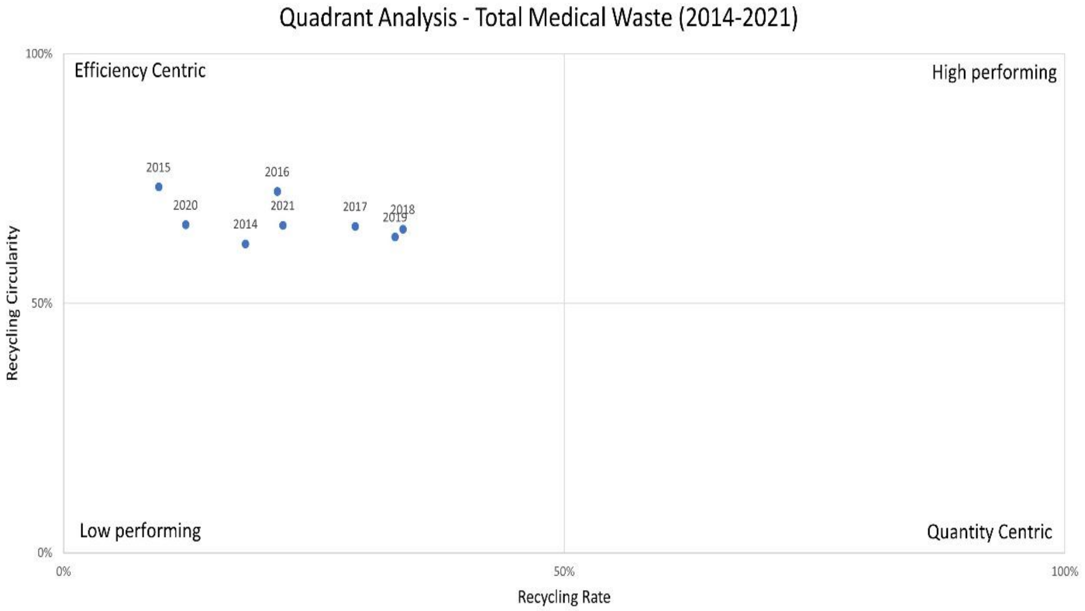

Figure 14. Quadrant Analysis for total medical waste

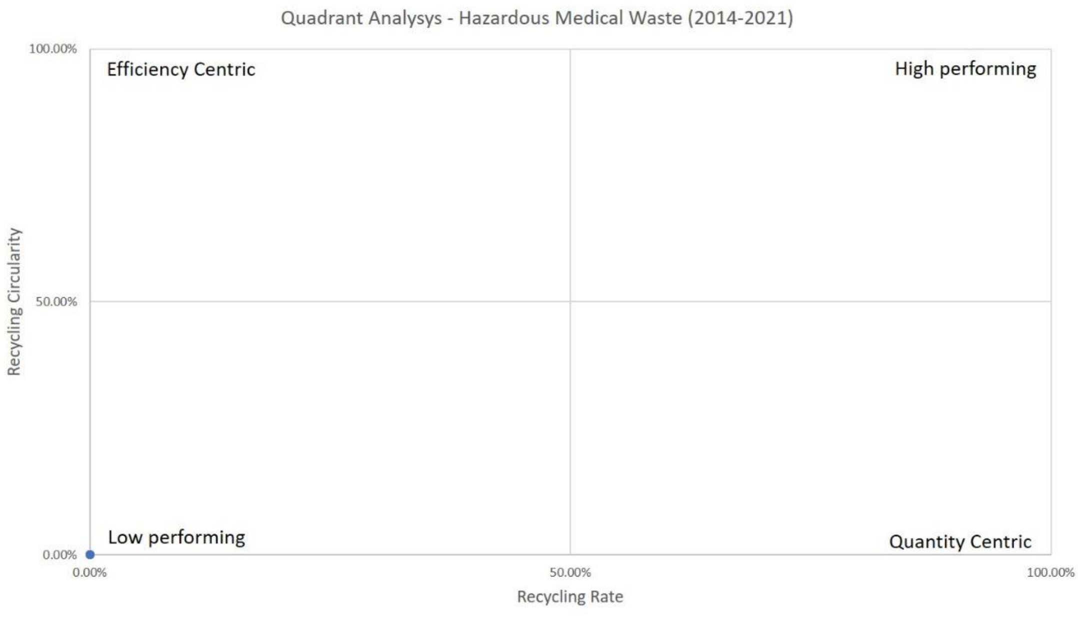

Figure 15. Quadrant Analysis for hazardous medical waste

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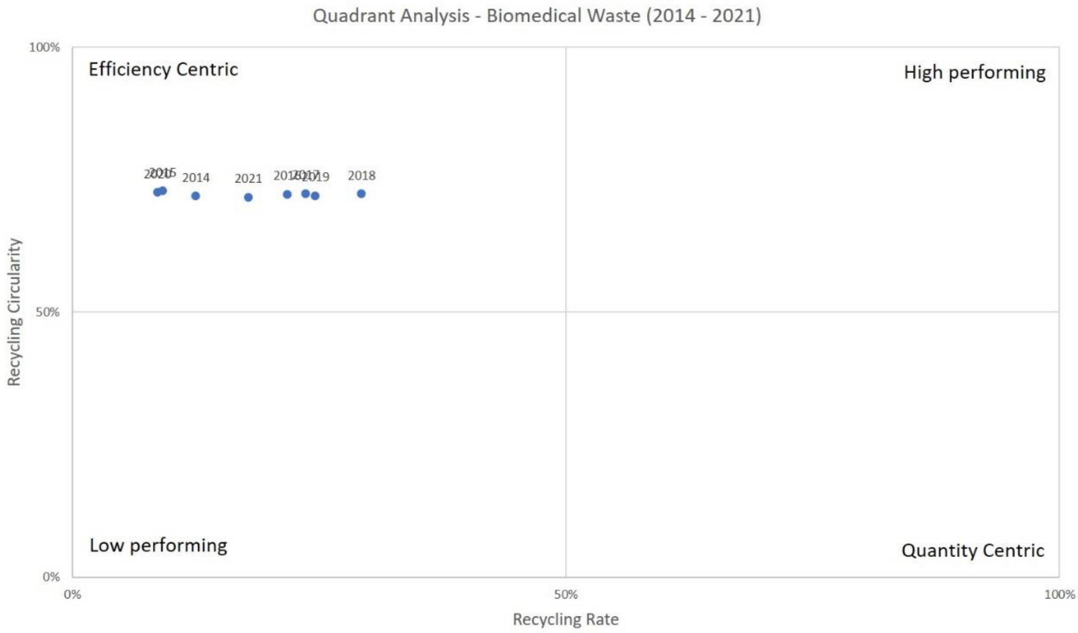

Figure 16. Quadrant Analysis for biomedical waste

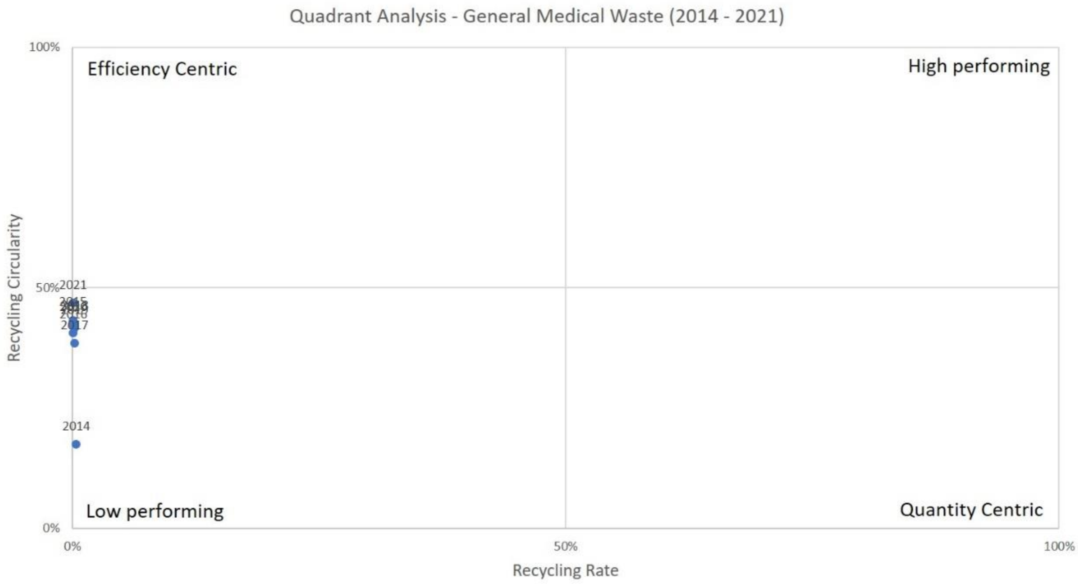

Figure 17. Quadrant Analysis for general medical waste

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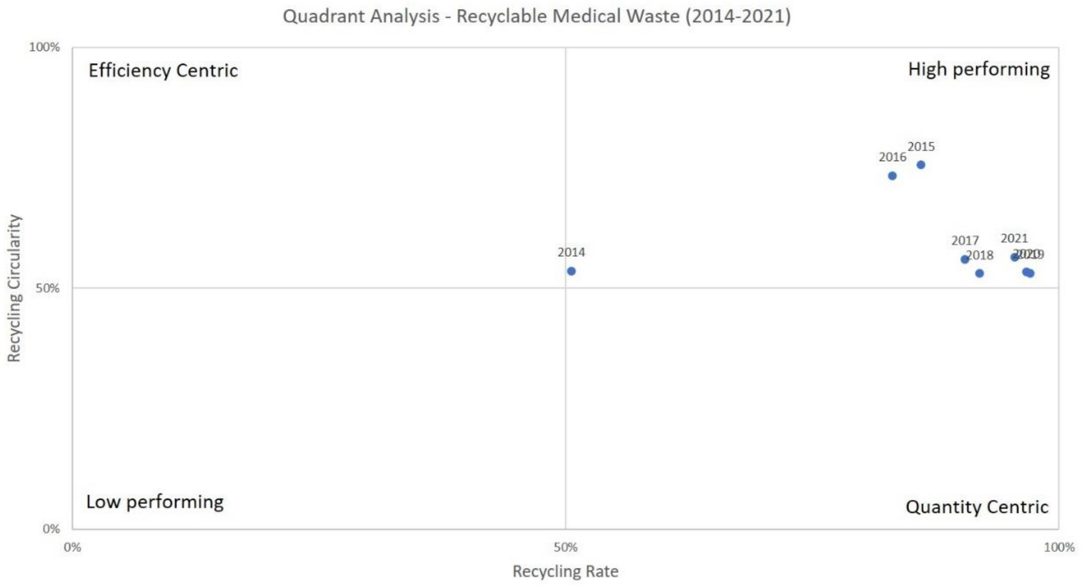

Figure 18. Quadrant Analysis for recyclable medical waste

4.2.5.3 Circularity level distribution analysis

Figure 19 to 23 are the circularity level 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 5.

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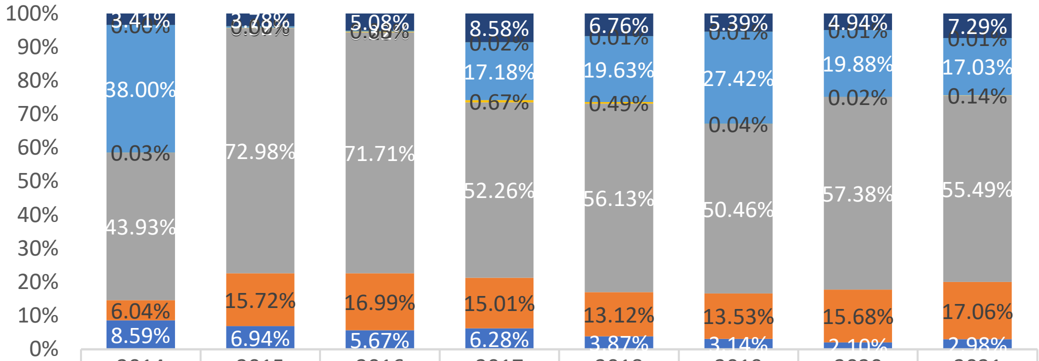

	2014	2015	2016	2017	2018	2019	2020	2021
CL-1	3.41%	3.78%	5.08%	8.58%	6.76%	5.39%	4.94%	7.29%
CL-2	0.00%	0.00%	0.03%	0.02%	0.01%	0.01%	0.01%	0.01%
CL-3	38.00%	0.52%	0.32%	17.18%	19.63%	27.42%	19.88%	17.03%
CL-4	0.03%	0.07%	0.20%	0.67%	0.49%	0.04%	0.02%	0.14%
CL-5	43.93%	72.98%	71.71%	52.26%	56.13%	50.46%	57.38%	55.49%
CL-6	6.04%	15.72%	16.99%	15.01%	13.12%	13.53%	15.68%	17.06%
CL-7	8.59%	6.94%	5.67%	6.28%	3.87%	3.14%	2.10%	2.98%

CL-7 CL-6 CL-5 CL-4 CL-3 CL-2 CL-1

Figure 19. Circularity level distribution for total medical waste

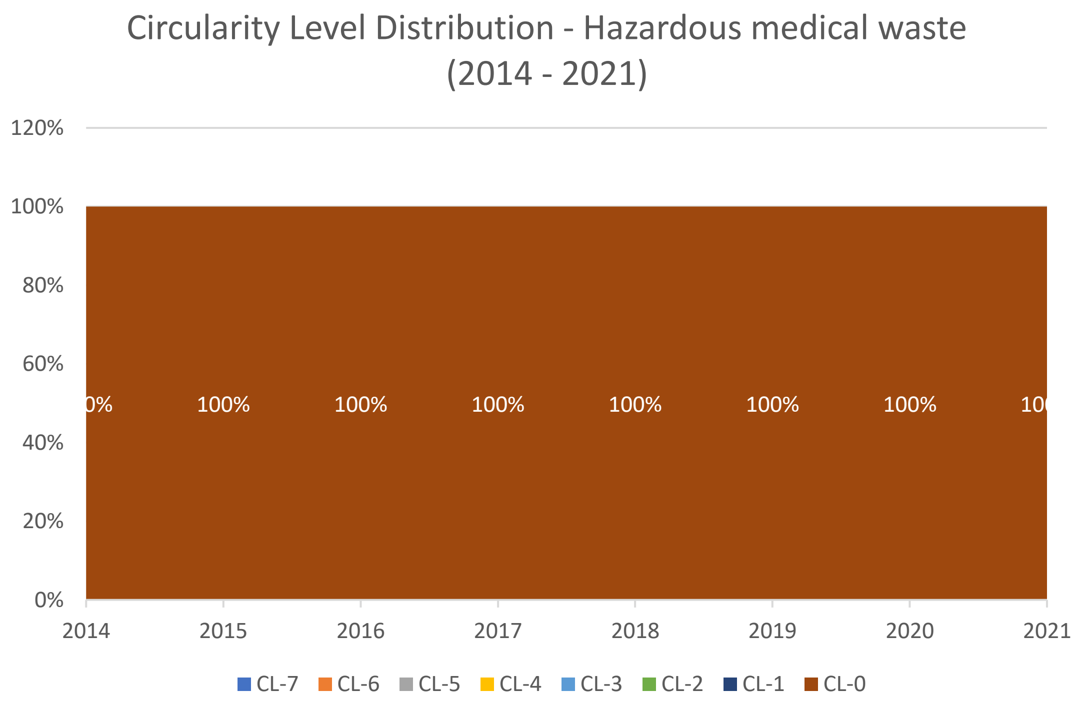

Figure 20. Circularity level distribution for hazardous medical waste

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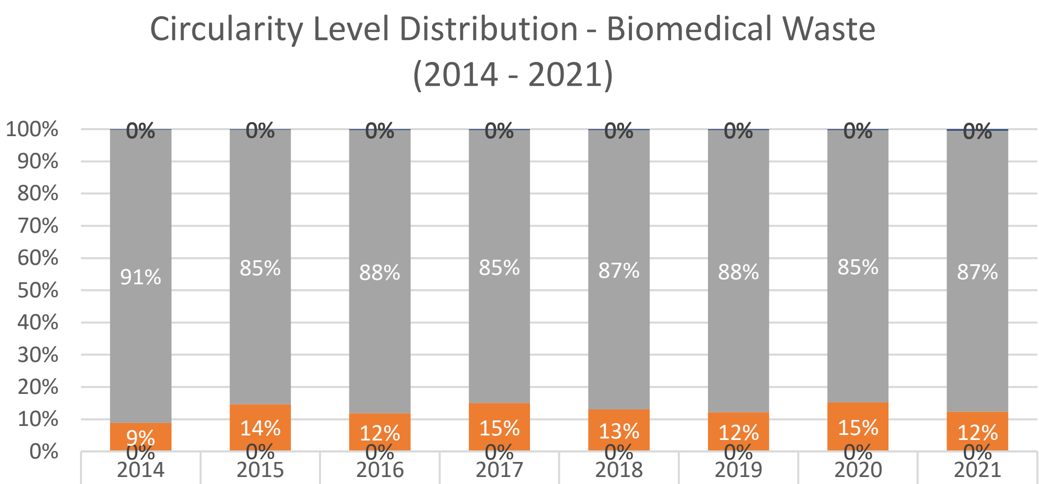
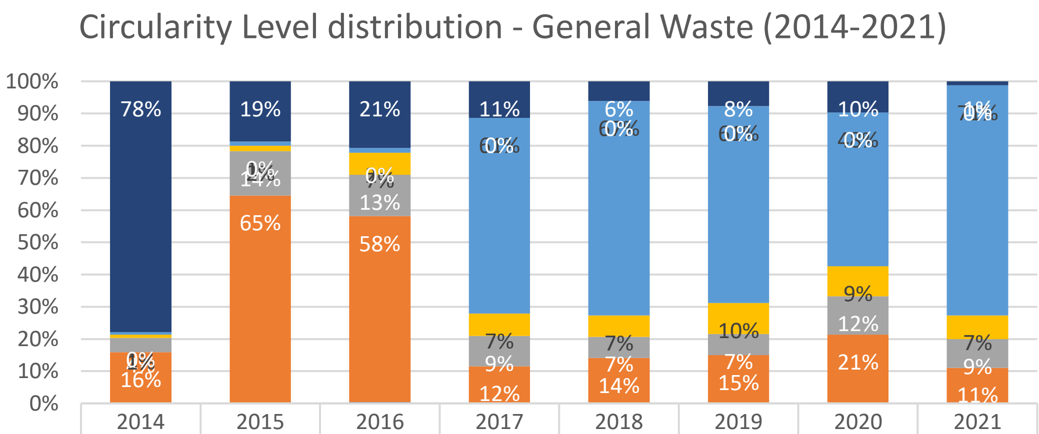


	2014	2015	2016	2017	2018	2019	2020	2021
CL-1	0%	0%	0%	0%	0%	0%	0%	0%
CL-2	0%	0%	0%	0%	0%	0%	0%	0%
CL-3	0%	0%	0%	0%	0%	0%	0%	0%
CL-4	0%	0%	0%	0%	0%	0%	0%	0%
CL-5	91%	85%	88%	85%	87%	88%	85%	87%
CL-6	9%	14%	12%	15%	13%	12%	15%	12%
CL-7	0%	0%	0%	0%	0%	0%	0%	0%

Figure 21. Circularity level distribution for 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%

Figure 22. Circularity level distribution for general medical waste

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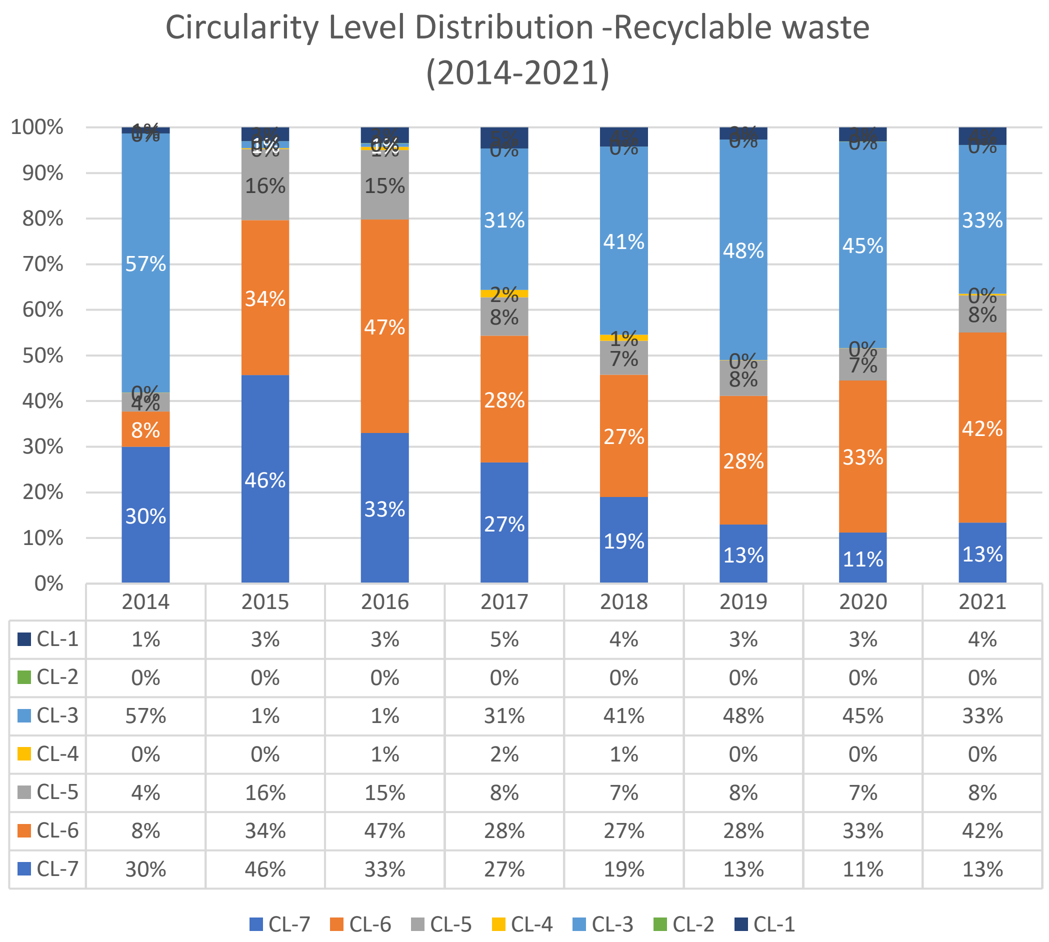

	2014	2015	2016	2017	2018	2019	2020	2021
CL-1	1%	3%	3%	5%	4%	3%	3%	4%
CL-2	0%	0%	0%	0%	0%	0%	0%	0%
CL-3	57%	1%	1%	31%	41%	48%	45%	33%
CL-4	0%	0%	1%	2%	1%	0%	0%	0%
CL-5	4%	16%	15%	8%	7%	8%	7%	8%
CL-6	8%	34%	47%	28%	27%	28%	33%	42%
CL-7	30%	46%	33%	27%	19%	13%	11%	13%

Figure 23. Circularity level distribution for recyclable medical waste

4.2.6 Key findings

4.2.6.1 Overall performance for total medical waste

Figure 9 presents three distinct performance trends observed, including low and fluctuating recycling rate, a consistently high and stable recycling circularity, and gradual increase in the DCPI. The significant decrease in recycling rate in 2020 can be attributed to the surge in total medical waste generation during the beginning of the pandemic, which later returned to normal levels. Several factors influencing the WM performance are observed.

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First, the high and stable recycling circularity indicates the strict regulatory requirement that prevent the use of lower circularity level waste treatment processes. This is further supported by Figure 14, which shows the performance of total medical waste falling within the "efficiency centric" quadrant.

Second, the gradual increase in DCPI and the sharp decline in recycling rate suggest limited waste recycling waste capacity to handle the surge in waste generation. The correlation coefficient of -0.4852 between recycling rate and recycling circularity 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.

4.2.6.2 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.

4.2.6.3 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

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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.

4.2.6.4 Overall performance for General medical waste

General medical waste constitutes the second largest group, accounting for 13.5% of the total waste generation. Figure 12 shows the combination of relative high circularity performance with extremely low recycling rate of between 0.06% to 0.39%. This is unexpected considering the non-hazardous nature of the waste and its recycling potential. Figure 17 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.

4.2.6.5 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 50.58% to 95.48% over the 8-year period reflects a strong policy drive towards recycling waste under this category. However, the stagnant recycling circularity and DCPI indicate a focus primarily on the quantity rather than the quality of

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waste treatment during this period. Figure 18 shows the CPI falling within the "high performing" quadrant, aligning with the non-hazardous and highly recyclable nature of this waste category.

4.2.6.6 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 reveals 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 recycling circularity observed for most waste categories. However, the requirement over recycling through higher circularity level 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 general medical waste are incinerated rather than recycled.

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

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circularity performance.

Policy plays a significant role in the significant increase in recycling rate 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 recycling rate.

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 DCPI 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 DCPI, suggests that the waste generation exceeded the existing recycling capacity, leading to a decline in the recycling rate.

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Chapter 5 Discussions

The results from the two case studies demonstrated the practical applications of the circularity performance concept for waste management performance evaluation tool. This chapter consists of comparisons with related studies, discussion on the feasibility of the indicators and processes introduced and the limitations of the evaluation framework.

5.1 Limitation of "recycling rate" as CE performance indicator

"Recycling rate" has long being utilized as WM performance indicator and has been shown by researches (Directive 94/62/EC 1994, Gutowsku et al., 2013 Di Maio, 2015) that using "recycling rate" as main CE indicator is inadequate and will lead to "inaccurate, misleading, wrong decision making and poor innovation". The limitation arises from the multidisciplinary nature of CE, which requires addition factors to be taken into account when assessing CE transition. CPI emerged as a response to this limitation by introducing the missing sustainability assessment component. Case study findings reaffirmed the aforementioned assertions.

In the first case study, the poor correlation coefficient between the "recycling rate" and "recycling circularity" for the 27 manufacturing sectors aligned with the assumption that quantity of recycling cannot be used as the sole indication of circularity.

In the second case study, in addition to the low negative correlation coefficient between "recycling rate" and "recycling circularity", there are other examples where

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using “recycling rate” as a sole WM performance indicator can potentially lead to misinterpretation. For instance, the recycling rate for total medical waste decreased from 20.98% in 2019 to 8.02% in 2020, suggesting a decline in performance. However, when considering the DCPI, it becomes evident that there was an actual increase in total volume of waste recycled. The performance of recyclable waste presents another scenario were relying on recycling as WM performance can be misleading. The significant increase in recycling rate over the 8-year period suggest overall improvement in sustainability. However, when examining the marginal improvement in recycling circularity and the decline in DCPI, 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 recycling rate. Simultaneously, it is evident that the introduction of the new indicators contributes to a better overall performance evaluation.

5.2 Application of "recycling circularity” for measuring waste management performance

“Recycling circularity” denotes the quality or efficiency aspect of the resource recovery process, complementing the conventional assessment that primarily relies on “recycling rate”, providing insights that are often overlooked when assessing solely on quantity-based evaluation.

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The outcomes derived from the two case studies on “recycling circularity” present a distinct perspective on the waste management practices that are not captured by “recycling rate” alone. The observed weak correlation coefficient observed between the numerical results of the two indicators underscores the independent nature of recycling quantity and quality. “Recycling circularity” sheds light on the waste generator’s choice of recycling options, indirectly reflecting the synergistic impact of various influencing factors, such as recycling cost, market demand and the availability of recycling technology.

5.3 The practical application of the circularity performance concept

The case studies presented herein exemplified the application of CPI for evaluating WM performance at national and sectoral level. CPI is designed as a practical assessment tool with advantages over similar WM performance assessment methods including reduced data requirements, applicability at micro, meso and macro levels, and the ability to complement the popular “recycling rate” indicator commonly used in assessing industrial WM performance. However, it is acknowledged that the simplicity of the CPI may result in less precise outcomes. Moreover, certain aspects, such as the determination of relative circularity level, warrant further improvement in the future research endeavours. These areas of refinement are crucial to enhance the accuracy and effectiveness of the CPI.

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5.4 The practical implication of DCPI

The DCPI is introduced as a solution for potential misinterpretation that may arise when directly comparing CPI results across multiple assessment years, particularly in the presence of significant fluctuations in the total amount of waste generated caused by extreme event such as COVID-19 pandemic. For example, in the second case study, the CPI for total medical waste declined from 20.98% in 2019 to only 8.02% in 2020, suggesting a decline in circularity performance. However, this decline is attributed to the substantial decrease in the recycling rate caused by the surge in the total amount of waste generated in 2020. The results demonstrate that the DCPI enables performance assessment in terms of the absolute amount of waste recycled, which provides a perspective that is absent when evaluating through CPI's ratio-based approach.

5.5 Comparison with other waste hierarchy-based CE assessment methods

The waste hierarchy concept is widely adopted by environmental authorities worldwide as a fundamental principle in WM due to its recognized benefit in dematerialization. As a result, several CE assessments have been developed based on this concept, including the Material Circularity Indicator (MCI), Ternary Diagram and the Waste Hierarchy Index (WHI) as identified in the literature review. A comparison between WHI and CPI is drawn, as both are based on the philosophy that "different waste hierarchy operation makes different contributions to CE" and both are designed for regional WM

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performance assessment. It is observed that WHI values exhibit a strong correlation with "recycling rate," except in countries where waste to energy (WtE) practices are prevalent. Consequently. WHI fails to provide an independent perspective on the efficiency aspect of WM, unlike CPI. In addition, the computation of WHI involves assumption-based variables and scenario analysis to compensate for data gaps while CPI calculations rely solely on general waste management data. In this aspect, WHI can be more advantageous for policy formulation due to its incorporation of scenario analysis, whereas CPI only reflects the current status.

5.6 Limitation of "waste hierarchy" concept

While the waste hierarchy principle is widely embraced in waste management policy, it is acknowledged that this philosophy does not always indicate the best environmental option, as dematerialization does not always guarantee lower environmental impacts. (van Ewijk et al., 2016). However, studies have demonstrated a strong connection between the waste hierarchy and CE concepts in terms of optimizing resource intensity and employing a life cycle approach (Zhang et al., 2022), which is commonly employed by WM systems and adopted for WM performance assessment (Pires et al., 2019, Zhang et al., 2022). Ideally, the environmental performance should be evaluated based on the absolute environmental impact of each waste treatment process. However, such data is not readily available in general waste management system and

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requires additional research or modelling efforts. In contrast, waste management data aligns well with waste hierarchy-based assessment methods due to compliance with existing policy. Consequently, CPI aims to assess CE performance using WM data and thus incorporates the waste hierarchy as an assessment criterion. In the future, CPI could be further enhanced by incorporating additional efficiency parameters that allow for flexible adjustments based on known environmental impact. However, this can only be accomplished with comprehensive WM data which is often lacking.

5.7 CE assessment criteria for industrial waste management

The literature review reveals a lack of widely acknowledged, commonly agreed-upon, or standardized index for waste management (WM) systems across countries and industrial sectors. To abridge this gap, this research undertook a compilation of diverse CE definitions and incorporated key insights from previous studies to develop a set of assessment criteria. While not perfect, it is anticipated that the formulated assessment criteria offer an integrated perspective on the existing research landscape and serve as a catalyst for further discussions on evaluating sustainability of WM.

5.8 "Waste characterization" for obtaining industry-specific insight

The "waste characterization" process is introduced in the second case study and has successfully revealed the differences in WM performance among different medical waste groups due to the differences in waste characteristics. This finding underscores the

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importance of considering the unique characteristic of waste categories when formulating industry-specific circular economy strategy.

5.9 Limitations

Application condition: This assessment is applicable to countries undergoing a transition from a recycling-based society to a circular economy. It relies on industrial waste generation and treatment data, which is typically available from well-managed industrial waste management systems commonly found in developed countries. However, if data is incomplete due to issues such as illegal dumping, exportation, or inadequate industrial waste management systems, further investigation may be necessary to estimate waste generation and the corresponding treatment methods.

Factors not considered: The assessment primarily relies on the waste hierarchy concept, where the sustainability priorities of waste treatment options significantly impact the assessment results. The complete life cycle of industrial waste encompasses waste collection, transportation, and treatment. As a result, factors such as transportation distance, variations in recycling process efficiency, and market demand for recycled resources directly affect the overall efficiency.

Assessing waste generation: The European Union's monitoring framework for the circular economy categorizes "waste generation" within the domain of "production and consumption." Consequently, it falls outside the scope of the assessment, despite its

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significant importance in the waste hierarch.

Comparison of result: a comparison of the results from different studies will be possible through the adoption of the identical circularity level scheme. For comparison between different data sources, calculations need be performed at reduced levels (lower circularity levels) to accommodate the least comprehensive dataset.

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Chapter 6 Conclusions

Proper management of industrial waste is essential for achieving a circular economy transition, necessitating an effective framework for monitoring and evaluating waste management performance. Despite numerous studies on the sustainability of waste management, there is still considerable uncertainty regarding the alignment of WM activities with the principles of CE. Furthermore, there is a need for a holistic and multidisciplinary CE assessment method to evaluate WM performance, as the dominant indicator, the "recycling rate", has been found to be have limitations in accessing CE alone. Additionally, the existing performance evaluation framework fails to provide the industry-specific insights necessary for formulating feasible CE transition strategies.

The circularity performance concept developed by this research allows assessing environmental, economic and social benefits of waste management, including waste hierarchy, economic value and longevity by means of the newly introduced indicator "recycling circularity." "Recycling circularity" complements the quantitative assessment by the "recycling rate" by considering the qualitative aspect of recycling operations. This integrated assessment approach covers both the quantitative and qualitative dimensions of waste management.

The circularity performance index allows application of existing waste management data without additional research efforts. It is presented as a single number and can be

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applied at different levels (micro, meso and macro) and to specific industry. Additionally, the proposed evaluation employs quadrant analysis and circularity level distribution providing policymakers or business owners with a clear visual display of information.

However, it is important to note that CPI currently focuses solely on waste recycling operations occurred after waste generation. The complete industrial waste life cycle encompasses waste generation, transportation and treatment of waste. At present, the CPI does not consider the impacts of waste generation and transportation with the underlying assumption that the treatment facility of the same kind operates at the same efficiency. Further researches are needed to determine the impacts of these activities and how to incorporate them into the calculation of the CPI.

Contrary to the policy focus on achieving high waste management performance through improving "recycling rate", the results of the case studies demonstrate otherwise. At the national level, despite a high average national recycling rate of 83%, there is room for improvement in the manufacturing sector, as indicated by the circularity class distribution showing that 16% of the waste is recycled for land-related applications (CL1), such as land reclamation and soil remediation. Similarly, at the industry level, sectors with extremely high recycling rate may perform poorly in terms of recycling circularity due to a concentration of waste treated with low circularity level treatment methods. Conversely, there are sectors with low recycling rates but perform well in terms of

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recycling efficiency. These findings highlighted three key points: first policymakers should consider that the essence of the circular economy is not just recycling but optimizing resource intensity; and second, attention should be given to the availability of recycling infrastructure and the cost of recycling, which are the two main factors influencing waste producers' decisions. A low recycling rate coupled with high recycling circularity may be attributed to a lack of cost-effective and highly efficient recycling options. For policy analysis, it is essential to consider the differences in the waste generated by various industries in order industry-specific insights. These insights can contribute to the formulation and implementation of CE transition policy or strategy.

However, it is important to note that the assessments in this study is 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 waste management assessment and facilitate better formulation of CE transition strategy and policy.

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Appendices

Appendix A – Inventory of waste recyclng processes in Taiwan

Taiwan EPA's industrial waste report and management system contains a list of 20 recycling processes as shown in Table A-1.

Table A-1. Inventory of waste recycling processes

Category	Code	Name	Description
Recycling and reuse	R01	Recycling of waste through channels certified by the waste fund management board	Recycling of listed recyclable waste announced by the waste recycling fund management board through certified channels
	R02	Recycling of waste as raw material	Used as a raw material of a product
	R03	Recycling of waste as an ingredient or additive	Used as a material or additive for other purposes (such as graded aggregates)
	R04	Recycling of waste as fuel	Used as a material for energy generation through combustion
	R05	Recycling of waste as feedstock	Used as direct animal feedstock
	R06	Recycling of waste as fertilizer	Used as a nutrient for cultivating plants
	R07	Recycling of waste as an engineering filling material	Used as filling material for engineering purposes
	R08	Recycling of waste for improvement of land (soil) quality	Improved quality of land (soil) through the recycled waste
	R09	Recycling of waste as reusable land	The transformation of land unfit for farming into land that can be used for farming
	R10	Recycling of waste for land reclamation	The transformation of land unfit for farming into land that can be used for farming through scientific methods
	R99	Recycling for other purposes	Reuse in applications recognized by other competent central authorities
Reuse of renewable resources	G01	Reuse of renewable resources	Direct reuse of a renewable resource without changing the state of the original material, or use after restoring the original function or part of the function through appropriate procedures
	G02	Reuse of renewable resources as raw material	Used as raw material for making products
	G03	Reuse of renewable resources as material	Used as a material or an additive for other purposes (such as graded aggregates)
	G04	Reuse of renewable resources as fuel	Used as a material for energy generation through combustion
	G05	Reuse of renewable resources as feedstock	Used as direct animal feedstock
	G06	Reuse of renewable resources as fertilizer	Used as nutrients for cultivating plants

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Category	Code	Name	Description
	G07	Reuse of renewable resources as filling material	Used as filling material for engineering purposes
	G08	Reuse of renewable resources for soil remediation	Soil quality improvement through the use of renewable resources
	G99	Reuse of renewable resources for other purposes	

Source: Taiwan Environmental Protection Administration, 2021, "Waste and renewable resources code" https://waste1.epa.gov.tw/NMS40/_res/FileLoad.ashx?i=E28B60160D56F706

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Appendix B – The EU Circular Economy Monitoring Framework

The European Union adopted a set of 10 indicators to monitor the transition towards a circular economy[1]. The indicators are grouped into four stages intended to cover the entire life cycle of a resource: (1) production and consumption, (2) waste management, (3) secondary raw material and (4) competitiveness and innovation. The circularity indicator in this study is used to examine how waste resources are treated to allow further resource circulation that takes place at the waste management stage. Waste minimization, which is also an important aspect of a circular economy, is not included in this research as it takes place during the production and consumption stage.

[1] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52018DC0029

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