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Original Research

A recycling technology selection framework for evaluating the effectiveness of plastic recycling technologies for circular economy advancement

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ABSTRACT

Despite progress in plastic waste recycling technologies, global plastic waste recycling rates remain disappointing. This problem not only suggests an underutilization of existing recycling technologies but also hinders resource utilization, the circular economy, and sustainable manufacturing. Several studies have proposed addressing this issue by evaluating recycling technologies based on recycled waste volume. However, such single-indicator methods often overlook other critical factors and, thus, may not provide holistic assessments. Additionally, existing methods for evaluating or comparing different recycling technologies are often complex and time-consuming. In contrast, other studies have proposed hundreds of indicators for assessing the effectiveness and suitability of recycling technologies, further complicating the selection process. Consequently, recyclers and other stakeholders often struggle to identify the most effective and suitable recycling technologies for different plastic waste types and under specific conditions. To address these challenges, we propose the recycling technology selection framework (RTSF), a simple tool that enables easy visualization of relevant recycling indicators under five key pillars: economic, technical, environmental, social, and policy. By enabling recyclers and stakeholders to quickly identify, select, and visualize factors of interest from a large pool, the RTSF facilitates qualitative comparison and enhances the evaluation of the effectiveness and suitability of multiple plastic recycling technologies. Lastly, the RTSF can serve as a preliminary tool and be integrated with other approaches to enhance the effectiveness of plastic recycling technologies.

1. Introduction

Despite various advancements in plastic recycling technologies for plastic waste like polyethylene terephthalate (PET), plastic waste pollution (Datta & Kopczyńska, 2016; Pongrácz et al., 2004a; Thiounn & Smith, 2020) and low plastic waste recycling rates remain a significant issue in many countries (Hahladakis & Iacovidou, 2018; Cruz Sanchez et al., 2020; Kranzinger et al., 2018). The growing spate of low plastic recycling results in environmental pollution that threatens humans and the environment. For example, low plastic recycling tends to increase the volume of plastic waste that ends indiscriminately in the environment and is eventually disposed of in landfills, thus increasing overall carbon emissions and contributing to the climate crisis. Additionally, low plastic recycling denies society the opportunity to re-integrate waste into the production loop as valuable materials, a situation that could be described as a missed opportunity (EPA, 2019; Rahimi & García, 2017).

Persistent low recycling rates suggest ineffective application and non-optimization of existing recycling technologies. This problem has also necessitated calls for evaluating recycling technologies to determine their suitability under varying socio-technical and economic conditions and enhance their effective deployment. However, existing methods for evaluating recycling technologies are often complex, skill-intensive, and time-consuming. Furthermore, various methods and hundreds of indicators exist to evaluate the strengths and weaknesses of different recycling technologies. However, these large pools of methods and indicators make evaluating the suitability and application of recycling technologies even more cumbersome. Thus, recyclers and other stakeholders often cannot effectively deploy recycling technologies, which may explain the resulting large amounts of unrecycled or ineffectively recycled waste.

The perennial low recycling rates, rising waste pollution, and underutilization of recycling technologies amid various existing

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recycling technologies and indicators necessitate simpler ways for evaluating recycling technologies toward improving their deployment, application, and impact. Thus, this paper introduces the recycling technology selection framework (RTSF), a user-friendly conceptual framework for visualizing indicators and qualitatively evaluating recycling technologies' effectiveness and suitability. The RTSF is simple, uncomplicated, and can be used to streamline and easily visualize indicators of interest under specific conditions from a large pool of indicators for evaluating recycling technologies.

This paper presents a state-of-the-art review (literature review in Section 2) that is organized into four sections. Section 2.1 briefly discusses the plastic pollution challenge and the role of waste recycling in achieving a circular economy. Section 2.2 focuses on some challenges of recycling technologies that necessitate frameworks for evaluating the effectiveness of recycling technologies. Section 2.3 highlights some benefits of evaluating the effectiveness and suitability of recycling technologies. Lastly, Section 2.4 examines examples of existing methods for evaluating recycling technologies and limitations often associated with them, which necessitate simpler frameworks for visualizing and analyzing recycling technologies. Next, the paper outlines the methodological approach of the study. The paper subsequently presents an overview and elements of the proposed RTSF and discusses its application. Finally, it concludes with some benefits and policy ramifications of the RTSF while highlighting its limitations and potential future research areas.

2. Literature review

2.1. Plastics, circular economy, and recycling

Plastics are widely used in various industrial processes, particularly in packaging, consumer and institutional products, and construction (Di et al., 2021; Geyer et al., 2017; Shah & Gangadeen, 2023). However, their widespread use in packaging, personal care items, and healthcare products has significant environmental repercussions (Fellner & Lederer, 2020; Ajani & Kunlere, 2019; Geyer et al., 2017). Plastics contributed to about 1% of the US carbon emissions (Posen et al., 2017) and 3.8% of global emissions in 2015 (Zheng & Suh, 2019), highlighting the urgent need for sustainable alternatives. The surge in global plastic production and consumption has led to an overwhelming increase in plastic waste (Al-Salem et al., 2009; Geyer et al., 2017; Smith et al., 2022; Williams & Rangel-Buitrago, 2022), straining waste management systems worldwide. Numerous studies have underscored the severity of the global plastic pollution crisis (Alassali et al., 2021; Burgess et al., 2021; Meys et al., 2020; Shah et al., 2019), attributing it to factors such as rampant plastic production and usage, inadequate waste collection, and ineffective management systems (Burgess et al., 2021; Jones, 2015; Kirchherr et al., 2018).

Despite growing awareness, the volume of global plastic production has continued to spiral upward, reaching nearly 400 million metric tons annually (Geyer et al., 2017) and potentially reaching 30 billion tons by 2050 (Geyer et al., 2017). This alarming trend is rooted in a production-oriented model that has long been the foundation of the global economy. This model relentlessly extracts raw materials to produce goods and services that, after consumption, eventually become waste (Ghisellini et al., 2016; Ness, 2008). This linear production model (Fig. 1) has resulted in rampant resource depletion, widespread pollution, and other detrimental consequences (Chen et al., 2022; Ajani & Kunlere, 2019; Park & Chertow, 2014; Preston, 2012; Yap, 2005).

Driven by growing public awareness of the devastating impacts of plastic pollution, coupled with mounting pressure from regulators and industry competition, concepts like circular economy, recycling, and sustainable manufacturing are gaining widespread traction (de Melo et al., 2022; McDonough & Braungart, 2002; Bennett, 1991; Boulding, 1966) (Fig. 2). These approaches minimize adverse economic, environmental, and societal impacts by emphasizing resource conservation, waste reduction, and product life cycle extension (Ghisellini et al., 2016; Park & Chertow, 2014). This shift promotes a move away from the unsustainable "take-make-dispose" mentality towards a more regenerative and sustainable approach.

However, despite the concepts above, human consumption always produces waste, which requires effective management approaches. Given these concerns and the need for integrated approaches, Boulding (1966) noted that the circular economy also hinges on effectively recycling waste (Fig. 2). The large amount of plastic used and the waste it creates support the need for sustainable manufacturing practices. However, one crucial way to reach this goal is to use resources efficiently, which includes recycling (Ateeq et al., 2023; WEF, 2016). Thus, recycling has emerged as a global priority and one of the pillars of the circular economy, sustainable manufacturing practices, and sustainable resource utilization.

Recycling presents many benefits that contribute to environmental protection and resource conservation. For example, it reduces pollution by diverting waste from landfills and incinerators, minimizing the release of harmful emissions and contaminants into the environment (Ateeq, 2023; Cleary, 2009; Priarone et al., 2016; Schwarz et al., 2021). Recycling also mitigates reliance on virgin raw materials, reducing the need for resource extraction and processing, often involving energy-intensive and environmentally

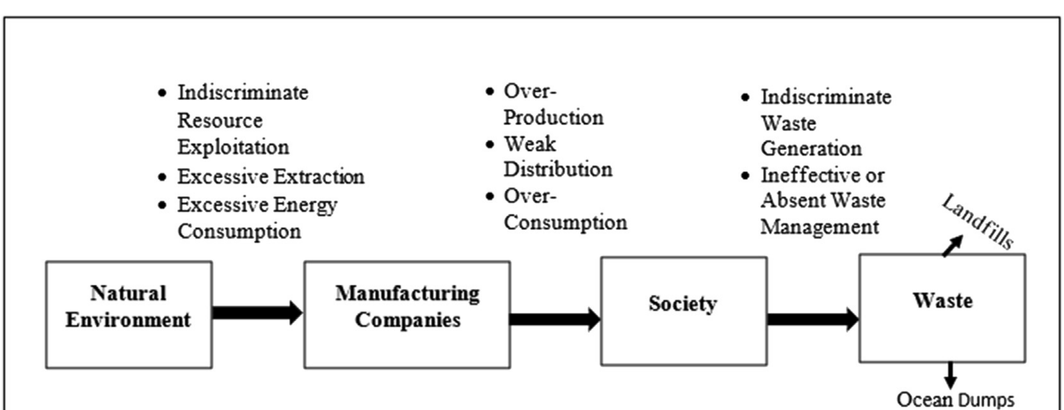

Fig. 1. An open loop system or linear economy.

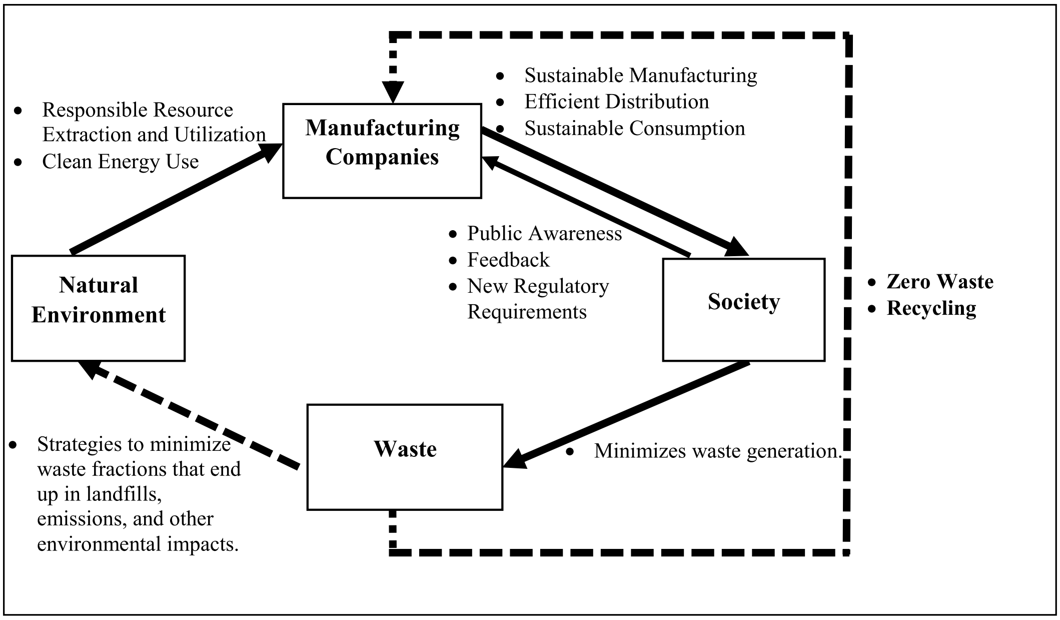

Fig. 2. A closed-loop system in a circular economy.

damaging practices. Furthermore, recycling may conserve energy and lower carbon emissions, promoting sustainable manufacturing practices and a cleaner environment. This transformative process transforms recyclable waste, such as plastics, paper, tires, and glass, into valuable new materials or monomers for reuse in production cycles, effectively closing the loop and minimizing waste generation. Recycling, therefore, stands as a cornerstone of a sustainable circular economy, fostering resource efficiency and environmental stewardship.

2.2. Some challenges of waste recycling

Despite the advancements in recycling technologies over the past few years, global recycling rates are still disappointing (Burgess et al., 2021; Di et al., 2021; EPA, 2020, 2022; Geyer et al., 2017). For example, only 10%–15% of plastic waste is recycled in the US and around 30% in the EU (Ragauskas et al., 2021), while a large part of the generated waste is incinerated, landfilled, or leaked into the environment (Benson, 2001; Bergmann et al., 2015; Cox et al., 2019; Di et al., 2021; Li et al., 2022). Various studies have identified factors such as cost, barriers, low collection rates, and insufficient social infrastructure as some of the contributors to the global issue of plastic waste recycling (Burgess et al., 2021; Ghisellini & Ulgiati, 2020; Heller et al., 2020; Jones, 2015; Kirchherr et al., 2018; Li et al., 2022; Preziosi et al., 2016; Vieira & Amaral, 2016).

Second, persistent low plastic waste recycling rates despite many recycling technologies that exist in the market today suggest inherently limited utilization of existing recycling technologies. For example, with various technologies in the market today, recyclers may struggle to select suitable options for specific waste types or conditions. Some studies measure the efficiency of recycling by focusing only on limited metrics like recycling rates, that is, the percentage of the volume of recycled waste, recovery, and diversion rates (Antonopoulos et al., 2021; Faraca & Astrup, 2019; Ventola et al., 2021). While some have championed the development of more advanced technologies to address the problem of low plastic recycling (Ghisellini & Ulgiati, 2020), it is essential to note that sophisticated recycling technologies alone may not necessarily lead to improved recycling rates or a more efficient plastic recycling industry.

Third, various plastic recycling technologies exist today, including incineration, pyrolysis, hydrolysis, and mechanical grinding (Thiounn & Smith, 2020; Wu et al., 2022), each with unique strengths and drawbacks that impact their deployment and desirability. For instance, while mechanical grinding is generally more energy-efficient, it tends to degrade the material's mechanical strength, resulting in lower-quality recycled plastics (Al-Azzawi, 2015; Jang et al., 2022; Wu et al., 2022). Such limitations could potentially impact the market acceptance and uptake of such recycled products, thereby reducing the amount of waste that gets recycled. Moreover, mechanical grinding often necessitates extensive sorting systems, leading to increased energy costs and limiting the recyclability of materials.

Conversely, chemical recycling methods like hydrolysis and glycolysis also present unique challenges. For example, these methods may necessitate high temperatures, rendering them costly, unsuitable, and unsustainable for long-term application (Bartolome et al., 2012; Sinha et al., 2010). Some technologies might be relatively affordable but could result in high carbon emissions or require extensive maintenance, which could inflate overhead costs and impact the volume of recycled waste. These factors indicate that a given recycling technology suitable for certain types of waste or under specific conditions might not be appropriate for others. Therefore, there is a pressing need for methodologies to assess the effectiveness and suitability of recycling technologies for specific types of waste or under particular conditions.

Lastly, recycling technologies can have unintended negative environmental consequences, potentially reducing their overall benefits to humans and the environment (Faraca et al., 2019; Lee et al., 2016; Moazzem et al., 2021; Pongrácz et al., 2004b). Moreover, despite the noble goal of reducing waste through recycling, it can paradoxically lead to increased consumption and waste generation. For example, as recycling rates rise, so does the tendency to consume more, placing further strain on recycling facilities, landfills, and the environment (Ma et al., 2019; Popov et al., 2004).

Considering the above and other concerns, it is essential to carefully evaluate each recycling technology's specific requirements and limitations to determine the optimal approach under given circumstances. Amidst growing pressure from regulators, competitors, and consumers, even industries like recycling must address critical concerns about emissions, energy consumption, and efficiency. These mounting pressures serve as powerful incentives to drive improvements within the recycling sector. These challenges also highlight the need for frameworks for evaluating recycling technology to ensure a holistic and system-focused approach for effective recycling outcomes. Thus, evaluation frameworks are crucial for assessing and effectively deploying recycling technologies.

2.3. Benefits of evaluating the effectiveness and suitability of recycling technologies

Recent attention on sustainable practices such as the circular economy, sustainable manufacturing, and recycling (Alamerew & Brissaud, 2018) has spurred a growing emphasis on evaluating circularity effectiveness (Camacho-Otero & Ordoñez, 2017; de Oliveira et al., 2021; Roos Lindgreen et al., 2020) and developing metrics to measure various aspects of sustainability accurately and objectively (Kirchherr et al., 2017; Saidani et al., 2019). However, measurements and evaluations have also been widely applied in various aspects of sustainability studies, including product circularity measurement (Corona et al., 2019; Elia et al., 2017; Kusumo et al., 2022) and assessment of end-of-life waste treatment technologies (De Almeida & Borsato, 2019).

Evaluating the effectiveness of recycling technologies is essential for a variety of reasons. Firstly, such evaluations highlight the unique strengths of a given recycling technology compared to others. Secondly, they expose areas that need improvement. For instance, each recycling technology has limitations, such as high energy consumption or greenhouse gas emissions, which could reduce the overall benefits of recycling. Hence, an evaluation system can assist in identifying and integrating the advantages and limitations of each technology into decision-making processes. Thirdly, evaluations provide a consistent basis for comparing multiple recycling technologies based on specific properties or characteristics. Fourthly, evaluations play a crucial role in decision-making, enabling researchers to concentrate on specific issues related to recycling technologies Corona et al., 2019; Kusumo et al., 2022). These evaluations also yield valuable insights for product development, policy design, and strategy and could inform sound decision-making (Golinska et al., 2015). Lastly, effectively assessing these tools' suitability, effectiveness, and impact shapes public opinions and perspectives that impact the adoption of such technologies (Kusumo et al., 2022).

2.4. Some methods for evaluating recycling technologies' effectiveness and their limitations

As Alamerew et al. (2020) aptly observed, a single indicator cannot effectively measure or explain the circularity of recycling technologies. Thus, circularity frameworks (Fig. 3) often rely on multiple indicators, each measuring specific aspects of the technologies under scrutiny. This has led to the proliferation of hundreds of indicators that exist across various frameworks for measuring circularity (de Oliveira et al., 2021; De Pascale et al., 2021; Kristensen & Mosgaard, 2020; Corona et al., 2019; Pauliuk, 2018). Usually, researchers select key indicators that best represent specific areas of interest. However, despite the plethora of circularity evaluation tools and approaches, each has its limitations.

Studies have extensively focused on various vital aspects of circularity metrics, indicators, and measurements, including recycling and circular economy areas. For example, Saidani et al. (2019) comprehensively list various circular economy indicators. Hundreds and tens of indicators exist across multiple frameworks for measuring circularity (de Oliveira et al., 2021; De Pascale et al., 2021; Corona et al., 2019; Kristensen & Mosgaard, 2020; Pauliuk, 2018), often leading to confusion in selecting appropriate ones for specific studies (Behrens et al., 2015; Bell & Morse, 2008). As a result, different selection methods exist, and multiple indicators are often used within each framework (Fig. 3), with researchers typically choosing key indicators that best represent specific areas of interest.

Studies have also highlighted four different dimensions or levels of circular economy at which circularity solutions could be implemented (Table 1). Thus, various tools exist for measuring circularity at these different levels. For example, the product recovery multi-criteria decision tool (PR-MCDT) (Alamerew & Brissaud, 2017), material circularity indicator (MCI) tool (Ellen MacArthur Foundation, 2020), design method for end-of-use product value recovery (EPVR) (Cong et al., 2017), Circular business model set of indicators based on sustainability (CBM-IS) (Rossi et al., 2020), circular economy toolkit (CET) (CET, 2023), sustainable circular

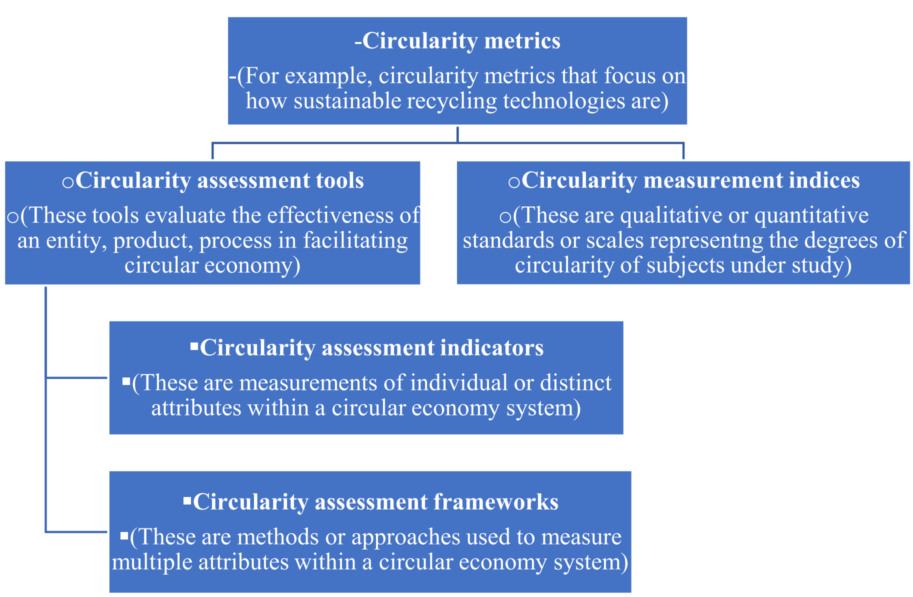

Fig. 3. A simple summary of some metrics used in measuring circularity.

Table 1
Dimensions of circular economy.

S/N	Levels of circular economy implementation	Description	Example	References
1	Nanosystem	Integrates circular economy into the manufacturing, handling, processing, or recycling of a single product, materials, or component	A product manufactured, handled, or processed in an industrial process but in a circular economy-compliant way	Woo & Whale, 2022; Nikkhah et al., 2021; Alamprese et al., 2021; Recanati et al., 2018; Pirlo et al., 2016; Klöpffer, 2005
2	Microsystem	Integrates circular economy within an individual sector or a company's internal extractive, manufacturing, product distribution, or recycling system	A circular economy-conscious extractive, manufacturing, product distribution, or plastic recycling company	Sahu et al., 2023; Sharma et al., 2021; González et al., 2021; Ginga et al., 2020
3	Mesosystem	Integrates circular economy between two or more extractive, manufacturing, product distribution, and recycling companies within a state or limited region	A circular economy-based collaboration between two or more extractive, manufacturing, product distribution, and recycling companies within a state or limited region	Wang et al., 2023; Stillitano et al., 2022; Garrido et l., 2023; Barros et al., 2023; Koçak et al., 2021; Mavi & Mavi, 2019
4	Macrosystem	Integrates circular economy between multiple extractive, manufacturing, product distribution, and recycling companies or sectors at the state, country, or international level	A circular economy-integrated extractive, manufacturing, product distribution, and recycling sector at the state, country, or international level	Mamghaderi et al., 2023; Banjerdpaiboon & Limleamthong, 2023; Stanković et al., 2021; Pacurariu et al., 2021; Iacovidou et al., 2021; Robaina et al., 2020; Giannakitsidou et al., 2020; Velenturf et al., 2019; Mayer et al., 2019; Ferronato et al., 2019; Van Eygen et al., 2018.

index (SCI) (Azevedo et al., 2017), and circular economy indicator prototype (CEIP) (Cayzer et al., 2017) could measure circularity of the product (nano) and micro levels. On the other hand, circulytics (Ellen MacArthur Foundation, 2020) and circle assessment are examples of process or company (or meso) level circularity measurement tools.

These tools, however, are characterized by various limitations (Corona et al., 2019; Elia et al., 2017; Linder et al., 2017; Saidani et al., 2017). An example is the PR-MCDT, a comprehensive framework for evaluating and selecting the most suitable end-of-life product recovery strategies (Alamerew & Brissaud, 2017). It considers various factors, including economic, environmental, and social indicators, to ensure that the chosen strategy is sustainable and beneficial for all stakeholders. Although the PR-MCDT assesses circularity for end-of-life scenarios, it does not address the product's in-use phase (Trollman et al., 2021). Conversely, the MCI tool, though widely used, measures only product and material circularity and does not apply to production process circularity (Trollman et al., 2021). Similarly, the end-of-use product value recovery (EPVR) is used to select applicable end-of-life waste management methods that maximize recovery cost reduction and improve the resulting product design (Cong et al., 2017). However, one of the critical shortcomings of the EPVR is that it does not evaluate product circularity (Cong et al., 2017; Matos et al., 2023).

Existing methods for evaluating recycling technologies are often quantitative, highly technical, and time-consuming, hindering fast decision-making. Numerous evaluation tools are often difficult to understand and conceptualize. There is also a lack of consensus on which indicators to evaluate or how to do so (Bîrgovan et al., 2022; Kristensen & Mosgaard, 2020), and confusion often arises in choosing appropriate ones for specific studies (Behrens et al., 2015; Bell & Morse, 2008).

Furthermore, a dearth of user-friendly frameworks exists for visualizing indicators of interest from the extensive collection of potential indicators. The lack of adequate visualization frameworks hinders the ability to evaluate recycling technologies promptly and efficiently. This gap also leaves decision-makers grappling with the challenge of choosing the most suitable technology for specific circumstances, a problem often aggravated by time constraints, knowledge limitations, and resource scarcity. Thus, addressing this limitation is essential for improving the evaluation and selection of recycling technologies, ultimately contributing to more sustainable waste management practices.

To address this challenge, this paper proposes the RTSF, a simple visualization tool based on social, technical, environmental, economic, and policy indicators. The RTSF visualizes indicators of interest and facilitates comparative assessments of recycling technologies within the broader context of waste management systems and sustainability goals, providing a structured and transparent evaluation process. The RTSF's use of a simple set of indicators and an easy-to-use interface makes it highly adaptable to the needs of various stakeholders in evaluating and selecting appropriate recycling technologies. This user-friendly design allows stakeholders with different levels of technical expertise to utilize the RTSF to make informed decisions effectively. The framework's ability to provide qualitative evaluations further enhances its practical utility, empowering decision-makers without requiring specialized technical expertise. Its simplicity, usability, and holistic approach make it an accessible and helpful resource for stakeholders seeking to make informed decisions about adopting, implementing, and promoting sustainable recycling solutions. This framework can serve as a valuable tool for improving recycling technologies, enhancing overall efficiency, and guiding future research on recycling technology evaluation.

3. Methodology

The study employed a mixed method that included an extensive literature review, a strict screening process, consideration of the timing of relevant research, and analytical design. This approach ensured that the RTSF was based on a strong foundation of existing knowledge and included broad views on evaluating the sustainability of plastic recycling technologies. The study was carried out in three stages. The initial phase involved an extensive literature review to gather insights from existing plastic recycling technology evaluation research. Three comprehensive searches were conducted across various academic publishers and databases, including Scopus, PubMed, Semantic Scholar, Taylor and Francis, and Web of Science. Employing a carefully selected set of keywords, such as "types of plastic recycling technologies," "circularity indicators," "limitations of recycling technologies," "evaluation of recycling technologies," "measuring circularity," and "how to measure the sustainability of recycling technologies," resulted in an initial pool of over 400 potentially relevant publications.

A screening process was undertaken to ensure the alignment of the selected literature with the specific focus of the RTSF on circular economy indicators, evaluation methods, and sustainability measurements of recycling technologies. The abstracts, methods, and conclusions of each identified publication were meticulously examined to determine their relevance to the study's objectives. This step narrowed the selection to over 100 papers that provided valuable insights into evaluating plastic recycling technologies.

The keyword search prioritized publications published between 2000 and 2023, acknowledging the historical evolution of evaluation methods was deemed essential. This approach allowed for the inclusion of a few exceptional publications that offered strategic historical contributions to the development of methods for evaluating the sustainability of plastic recycling technologies. The selected publications employed diverse analytical methods and frameworks, reflecting the multifaceted nature of evaluating plastic recycling technologies. Overall, the publications employed in the study included various analytical methods and frameworks, including quantitative analysis, multi-decision analysis, and conceptual studies.

In the second stage, we identified common circularity indicators and evaluation methods from the selected papers. This process revealed several challenges with the current methods used to assess the effectiveness and suitability of recycling technologies. For instance, while hundreds of circular economy indicators are available for evaluating recycling technologies (De Pascale et al., 2021; Saidani et al., 2019), the sheer number often complicates selecting suitable recycling indicators for specific objectives. Additionally, the evaluation methods are often complex, time-consuming, and require advanced skills. Visualizing the relationships among various indicators also poses a challenge. In the third stage, we focused on developing the RTSF, a user-friendly framework to visualize the relationships between two or more recycling technologies. It also allows for the qualitative evaluation of their effectiveness and suitability using selected indicators. These chosen indicators fall into five categories, divided across two main themes: input and output.

The RTSF is designed to facilitate the easy visualization of pertinent indicators for assessing the effectiveness of recycling technologies. It offers three key advantages. First, it assists in identifying factors (indicators) that could impact the effectiveness of their chosen recycling technologies. Second, it provides a flexible selection of indicators drawn from a list of common indicators identified in various curated studies, offering a thoughtful basis for their categorization. Lastly, researchers can select and compare specific indicators of interest based on their unique objectives. The RTSF presents a single, user-friendly layout where multiple indicators can be visualized simultaneously, enabling a qualitative comparison of the selected indicators (Fig. 4).

4. Results and discussion

The RTSF is a micro-level framework for assessing the suitability of recycling technologies, using selected indicators grouped under five main pillars: economic, technical, environmental, social, and policy (Tables 2 and 3, Fig. 4). It uses multiple measurable parameters, unlike the single-subject approach used in studies like Kytzia et al. (2004) and Wang et al. (2020). Its goal is to maximize recycling outputs while minimizing environmental and social impacts while complying with regulations in a specific area. The RTSF is flexible, allowing for selecting and comparing indicators based on the desired objective and scope.

This tool makes it easy to evaluate a recycling technology's desirability and suitability or compare multiple recycling technologies. These pillars are split into inputs and outputs (Tables 2 and 3, Fig. 4). Inputs include indicators related to materials and resources

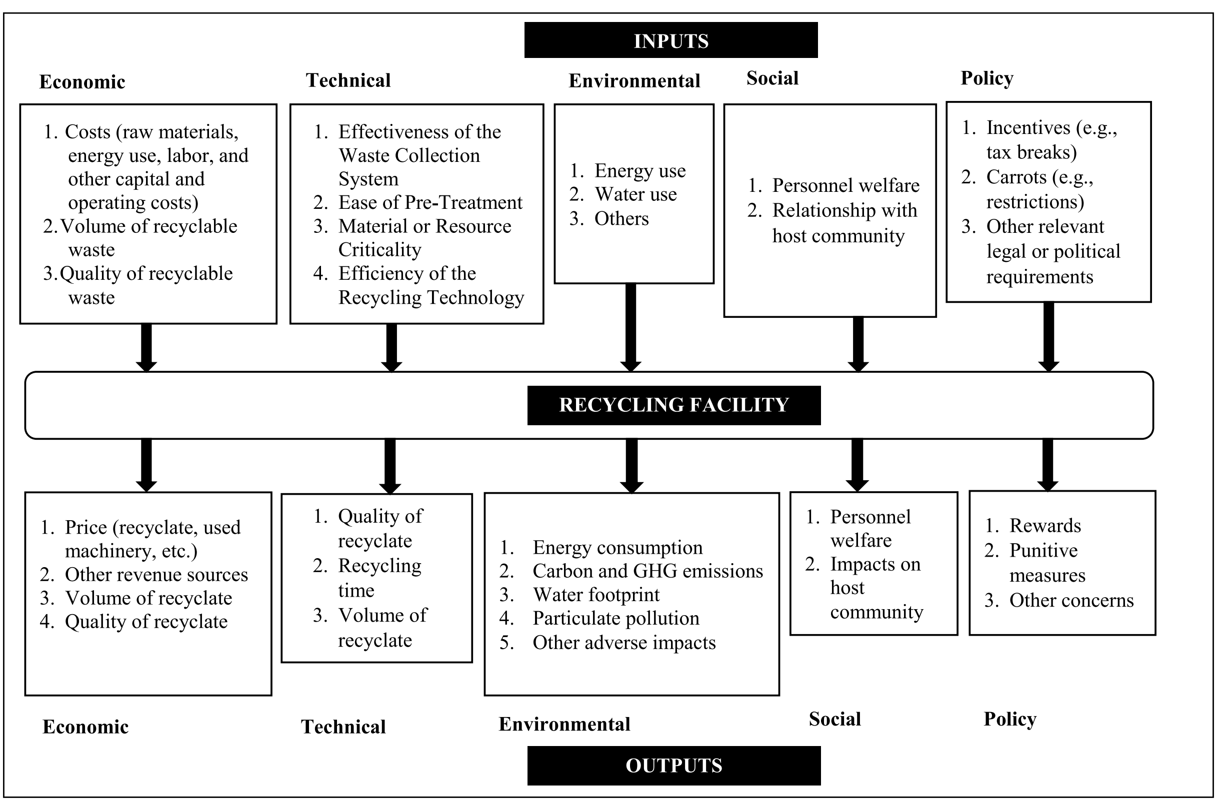

Fig. 4. Recycling technology selection framework (RTSF).

Table 2
Technical indicators for a recycling facility.

S/N	Determinants of recycling outcomes	Code	Optimal target
1	The effectiveness of the waste collection system	WCS	High
2	The ease of pre-treatment	EPT	High
3	Material or resource criticality	MRC	High
4	The efficiency of the recycling technology	ERT	High

used in the recycling facility, while outputs include products, byproducts, and the positive or negative impacts of the recycling process. However, the RTSF is not quantitative and does not involve complex mathematical analysis (Fig. 4). Instead, it is a framework that allows for visualization and qualitative comparison of relationships between two or more recycling technologies based on selected indicators. This user-friendly approach makes it accessible for both professionals and non-professionals.

4.1. Technical pillars (technology)

Technology plays a significant role in recycling outcomes (Antonopoulos et al., 2021) and is often a focal point in recycling planning and research. However, as the RTSF points out, technology is not the only crucial aspect of recycling. The technical elements of the recycling process typically include vital attributes such as the effectiveness of the waste collection process, the ease of pre-treatment (like sorting and preparation), material or resource criticality, and the effectiveness of the recycling technology itself (Tables 2 and 3).

4.1.1. Effectiveness of the waste collection system (WCS)

Recycling plastic waste is a holistic process that includes various stages, starting with waste collection. However, transportation is often necessary since waste is typically produced in locations far from the recycling facility (Mbuligwe & Kaseva, 2006; Tian et al., 2020). Collecting plastic waste shapes the form, volume, time, and shape of the waste batches that arrive at the recycling facility. This, in turn, influences the ease of pre-treatment and recycling processes and the quality and market price of the recycled materials. Suppose waste collection points are far from the recycling facility. In that case, it can lead to increased transportation and overall costs (Krugman, 1979), higher carbon emissions, and a greater risk of secondary environmental pollution (Abdelbasir et al., 2018; Tian et al., 2020; Tilmans et al., 2014). In many countries, ineffective waste collection systems are often the weak link in the waste value chain and can impact the entire process. Therefore, effective waste collection systems could improve recycling outcomes.

4.1.2. Ease of pre-treatment (EPT)

Plastic waste often arrives in mixed-state recycling facilities, requiring sorting and pre-treatment before recycling (Dahmus & Gutowski, 2007; Sultan et al., 2017). However, this pre-treatment stage can be costly, labor-intensive, time-consuming, and could

Table 3
Optimal targets for an effective plastic recycling technology.

S/N	Themes	Pillars	Examples of indicators	Examples of measurements	Targets
1.	Inputs	Economic	Costs (raw materials, energy use, labor, and other capital and operating costs)	Cost-benefit analysis (CBA), life cycle costing (LCC), input-output analysis, procurement controls	Low
		Technical	Volume of recyclable waste	Measuring equipment	High
			Quality of recyclable waste	Material testing, quality control	High
			Effectiveness of the waste Collection system	Input-output analysis, system analysis	High
			Ease of pre-treatment	Process optimization	High
			Material or resource Criticality	Principal component analysis, Feasibility studies	High
			Efficiency of the Recycling Technology	Process optimization	High
		Environmental	Energy use	Material flow analysis (MFA), life cycle analysis (LCA)	Optimum
			Water use	MFA, LCA	Optimum
			Others	MFA, LCA	Optimum
		Social	Personnel welfare	Labor laws, HR metrics, ESG	Optimum
			Facility-host community relations	Stakeholder analysis,	Optimum
		Policy	Incentives and carrots	Policy analysis, system evaluation, ESG	Optimum
			Emission limits and other standards or requirements	Environmental impact assessment (EIA), monitoring, and analysis	Optimum
			Policy and political environment	Policy analysis, system evaluation	Optimum
2.	Outputs	Economic	Costs (recyclate or recycled products)	CBA, LCC, Procurement controls	High
			Volume of recyclate	Measuring Equipment	High
			Quality of recyclate	Material Testing, Quality Control	High
		Technical	Quality of recyclate	Input-Output Analysis, Material Testing, Quality Control	High
			Recycling time	Process Optimization	
			Volume of recyclate	Measuring Equipment	High
		Environmental	Energy consumption	MFA, LCA	Low
			Carbon emissions	MFA, LCA	Low
			Water footprint	MFA, LCA	Low
			Particulate emissions	MFA	Low
			Other adverse impacts	EIA	Low
		Social	Welfare of personnel	Labor laws, Innovative H.R. Practices, ESG	Optimum
			Adverse impacts on host community and environs	Social and environmental justice, CSR, ESG	Low
		Policy	Rewards	Policy analysis, system evaluation	High
			Punitive measures	Policy analysis, system evaluation	Low
			Other concerns	Policy analysis, system evaluation	Low

expose workers to occupational hazards. In general, lengthy, complex, or expensive pre-treatment processes are undesirable as they can negatively impact waste recycling.

4.1.3. Material or resource criticality (MRC)

Resource criticality is a concept used to determine the value of a resource and the need for recycling. A resource's criticality depends on its abundance in nature and its importance to society (Dahmus & Gutowski, 2007; Morley & Eatherley, 2008). For instance, a resource with low abundance and high demand is considered highly critical, justifying the need for recycling efforts. Conversely, a resource with high abundance and low demand may have lower criticality, but its value could still increase due to the decision-makers interest in recycling it. Decision-makers' interest in a resource can be subjective and influenced by factors like toxicity, cultural significance, or historical importance. However, the higher the criticality of a resource, the greater its value and the stronger the case for recycling.

4.1.4. The efficiency of the recycling technology (ERT)

The efficiency of recycling technologies can be influenced by various factors such as the type of raw material, its volume, cost, and processing time. Common recycling technologies include pyrolysis, gasification, incineration, and mechanical recycling. These technologies can be intricate, involving heating and cooling systems, waste processing, and carbon capture components. However, their effectiveness is determined not only by technological advancements but also by human factors. For example, the skill level of personnel operating the equipment can significantly impact its efficiency. As a result, the output and suitability of similar recycling technologies for comparable waste types may vary over time or between different locations.

4.2. Economic and policy pillars

In addition to technical factors, economic considerations play a crucial role in the recycling industry. Recyclers and industry experts focus on the financial value of waste, recycling technologies, and recycled products, aiming to optimize economic outcomes (Table 3). Numerous studies have explored the techno-economic aspects of recycling and waste management. Volk et al. (2021) compared leading recycling technologies and found that a combination of mechanical and chemical recycling using pyrolysis yielded higher cost-efficiency and lower carbon emissions than incineration or individual methods.

Singh et al. (2021) reported that enzymatic degradation of PET waste could offer substantial economic benefits, while Peng and Shehabi (2022) highlighted the tremendous economic gains from e-waste recycling in the US However, Uekert et al. (2023) found mixed results when comparing various plastic recycling technologies' techno-economic and environmental impacts. They concluded that mechanical recycling, while financially rewarding, had mixed environmental impacts and produced recyclates of varying quality (Uekert et al., 2023). These studies suggest that prioritizing economic benefits over broader considerations could have adverse environmental and social consequences.

As awareness of the circular economy grows worldwide, various jurisdictions implement regulatory requirements to manage recycling processes. These regulations introduce new standards aimed at reducing waste, lowering carbon emissions, and increasing recycling rates, all while minimizing environmental and social impacts. However, these policy considerations are constantly evolving to keep pace with new realities, and these dynamics should be considered in recycling planning. For instance, in 2018, China banned the import of various types of waste, including plastic waste. This move disrupted global plastic recycling, which had previously relied heavily on China's substantial recycling capacity. In response, many countries are bolstering their recycling capacities and increasingly implementing policies to control carbon emissions, toxic releases, and environmental pollution from recycling technologies.

4.3. Environmental and social pillars

The recycling sector has grown substantially in numerous countries, fueled by government and private investments (Kinnaman et al., 2014; EEA, 2013). However, initiatives with good intentions can occasionally lead to unintended adverse outcomes or externalities, which are often overlooked in standard accounting procedures for recycling processes. For instance, excessive plastic use (Kunlere et al., 2019) and the oil sector have been linked to instances of primary, secondary, and tertiary pollution (Kalter & Passow, 2023; Gundry et al., 2017), resulting in environmental and social impacts. Similarly, recycling technologies, such as plastic waste recycling, can also contribute to environmental pollution (Ngamsang & Yuttitham, 2019; Tian et al., 2020) and have adverse effects (Vanhuyse et al., 2021; de Oliveira et al., 2021).

In the past, the hidden nature of recycling processes' environmental and social costs meant they were often ignored (Anshassi & Townsend, 2023). This was also partly because recycling processes are designed to reduce pollution, so there was little focus on their potential to cause pollution or other adverse environmental and social impacts. Some definitions of social cost often concentrate on monetary aspects, such as the portion of household income allocated to waste collection and recycling services (Callan & Thomas, 2001; Carroll, 2003; Kinnaman et al., 2014). However, several studies argue that the social costs of recycling extend beyond economic benefits (Kinnaman et al., 2014), leading to evaluations of whether recycling is environmentally and socially beneficial or harmful (Table 3). This broader perspective also includes environmental and social justice issues, such as groundwater pollution, property value distortion, particulate emissions, and community vulnerabilities related to recycling facilities. As a result, recent efforts prioritize pollution remediation costs over control and safety standards (Kinnaman et al., 2014) and estimate the environmental and social costs beyond economic aspects, considering externalities associated with recycling activities. Despite its complexity, considering these costs is crucial when setting up or operating a recycling facility.

4.4. Benefits of the RTSF

Efforts to increase waste recycling rates have often focused on developing frameworks for evaluating existing recycling technologies to improve their deployment. Furthermore, companies also often need to compare different plastic recycling technologies to find the most suitable one for specific conditions. However, while numerous studies have identified hundreds of indicators for evaluating recycling technologies, the vast number of these indicators can make it challenging to select the most relevant ones for the evaluation process (Corona et al., 2019; Pauliuk, 2018). It is also often difficult to determine which indicators to include or exclude during the evaluation process (Behrens et al., 2015; Bell & Morse, 2008).

Approaches for evaluating recycling technologies also face many other challenges. For example, existing methods are often time-consuming, debatable, and difficult to implement (Saidani et al., 2019). These methods also make visualizing or comparing the indicators challenging. Various existing frameworks often have a limited scope or require specific datasets, restricting their applicability (Trollman et al., 2021; Alamerew et al., 2020; Saidani et al., 2017). These limitations can hinder making immediate decisions often needed in real-world settings. However, recyclers and decision-makers require evaluation tools that provide quick, essential insights to make informed decisions about the effectiveness or suitability of various recycling technologies. Therefore, there is a need for non-complicated, complementary evaluation frameworks that can be easily compared.

To simplify the evaluation of recycling technologies, the RTSF offers a framework that helps narrow down the list of indicators and provides an easy way to visualize and compare the chosen indicators. This process can be expanded or repeated in cycles to include as many indicators as needed. It is a flexible tool that helps compare indicators of recycling technologies based on inputs and outputs, divided into five categories: economic, technical, environmental, social, and policy. The RTSF also offers a simple way to visualize the relationships between two or more recycling technologies.

It can be used as a starting point or in conjunction with other evaluation frameworks to determine the effectiveness or suitability of recycling technologies. The RTSF can serve as a cursor for subsequent evaluation steps, such as ranking the technologies based on the indicators of interest, which are often more complicated. The connections between the five pillars of the RTSF and the Sustainable Development Goals (SDGs) can be seen in Table 4.

4.5. Limitations of the RTSF

The RTSF represents a significant step forward in simultaneously visualizing indicators of interest and, thus, potentially addressing the challenges associated with evaluating plastic recycling technologies. However, despite its promises, the RTSF does have some limitations. Firstly, it does not provide empirical or quantitative measurements of the selected indicators. However, this limitation can also be viewed as a strength, underscoring the need for integration with other models and frameworks. As shown in Table 3, the RTSF depends on measurements from other models. For instance, the energy consumption of the recycling technologies (Priarone et al., 2016) could initially be measured by life cycle analysis (LCA). Then, their respective values can be incorporated into the RTSF.

Secondly, the RTSF helps select specific indicators from a list of indicators across five critical pillars (Fig. 4). However, it does not explain how to select specific indicators. Third, it also does not address the ranking of indicators or the trade-offs involved in the ranking process. Instead, the RTSF is subjective and leaves the decision of which indicators to include in the evaluation up to the recycler or decision-maker. Although this flexible approach could enhance the RTSF application, subjective decisions are often error-prone. So, the RTSF does not exhaustively resolve the question of what indicators to include and why. Lastly, the RTSF is designed as a preliminary or supportive screening tool, so its outputs are not definitive or conclusive in evaluating the effectiveness or suitability of two or more recycling technologies.

Despite its limitations, the RTSF can help initiate and simplify the typically complex evaluation process. For instance, the RTSF could assist recyclers and other users to conceptualize and visualize specific indicators from a large pool of indicators, providing a basis for qualitatively comparing these indicators. Therefore, it serves as an exploratory tool that generates valuable insights that can be combined with quantitative-based or other evaluation tools and frameworks to make a comprehensive and informed decision on the suitability and effectiveness of recycling technologies.

5. Conclusions and future research

Numerous calls have been made to enhance recycling technologies, boost low recycling rates, and promote a circular economy. As a result, several methods have been suggested to measure the recycling sector's circularity and assess the effectiveness of recycling technologies. However, these methods are often complex and challenging to implement. Despite the abundance of these evaluation methods, recycling rates are still low, and recycling technologies are not fully utilized. Therefore, there is a growing need to develop simple and easily implementable methods to evaluate the effectiveness and appropriateness of recycling technologies in specific situations.

Thus, this paper proposes the recycling technology selection framework (RTSF) to evaluate the effectiveness and suitability of recycling technologies. The framework helps select and visualize relevant indicators, providing a basis for comparing and determining suitability for recycling based on the recycler's or user's preferences. The RTSF holds potential as a beneficial resource for waste management experts in evaluating diverse waste management strategies and technologies. Waste managers can enhance their decision-making processes and improve waste management results by considering various economic, technological, environmental, social, and policy ramifications of recycling alternatives.

Table 4
Links between the 17 sustainable development goals (SDGs) and pillars in the RTSF.

SDGs	Goals	Pillars of the RTSF				
		Economic	Technical	Environmental	Social	Policy
1	No poverty	×				
2	Zero hunger	×				
3	Good health and well-being				×	
4	Quality education					×
5	Gender equality				×	
6	Clean water and sanitation			×		
7	Affordable and clean energy					
8	Decent work and economic growth	×				
9	Industry, innovation, and infrastructure		×			
10	Reduced inequalities				×	
11	Sustainable cities and communities				×	
12	Responsible consumption and production		×			
13	Climate action			×		
14	Life below water			×		
15	Life on land			×		
16	Peace and justice strong Institutions					×
17	Partnerships for the goals					×

The RTSF's ability to visualize and compare recycling systems can help the recycling industry achieve greater transparency and accountability. By simplifying the understanding of the performance of various recycling systems, the RTSF can encourage the adoption of best practices and assist in guaranteeing that recycling is done responsibly and sustainably.

Furthermore, policymakers can use the RTSF to engage with and increase awareness among various stakeholders in the recycling process, such as recyclers, industry participants, and the general public. The RTSF can assist in building mutual awareness of the most successful recycling technologies and promote their wider use by facilitating informed debates and cooperation. Lastly, policymakers can effectively use the RTSF tool to promote collaboration and exchange best practices in recycling technologies. Standardizing the evaluation process using instruments like the RTSF can encourage knowledge exchange among countries, allowing them to learn from one another's experiences and implement effective solutions. Such impacts could help increase recycling rates and facilitate more sustainable waste management systems.

However, the paper also acknowledges some drawbacks of the RTSF. For example, one common critique of many existing evaluation methods is their dependence on complex quantitative analysis, which can be inaccessible to those lacking the necessary skills. The RTSF addresses this issue by using subjective decision-making to choose or compare the effectiveness and appropriateness of indicators. However, such subjective steps could be vulnerable to biases and could be time- and situation-specific, thus limiting generability.

Finally, more research could focus on reducing the RTSF's subjectivity and, thus, widen the generability of its results. For example, quantitative research could improve generability, while observational research could assist researchers in identifying user preferences and expectations regarding the information on recycling technologies gathered through the RTSF. These insights could improve the RTSF to align with user needs and preferences better. More research could also explore the effects of implementing RTSF-suggested technologies across various settings or assess their influence on different waste streams, recycling rates, and waste reduction over time. Lastly, more studies could also investigate how the RTSF can be incorporated into wider circular economy models and frameworks to encourage sustainable resource management.

Declaration of competing interest

The authors state that they do not have any recognizable conflicting financial interests or personal connections that may have seemed to affect the research presented in this paper.

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